■ CRACKING DOWN ON SADDAM'S BIOLOGICAL WEAPONS ■

MIT'S
TECHNOLOGY
REVIEW



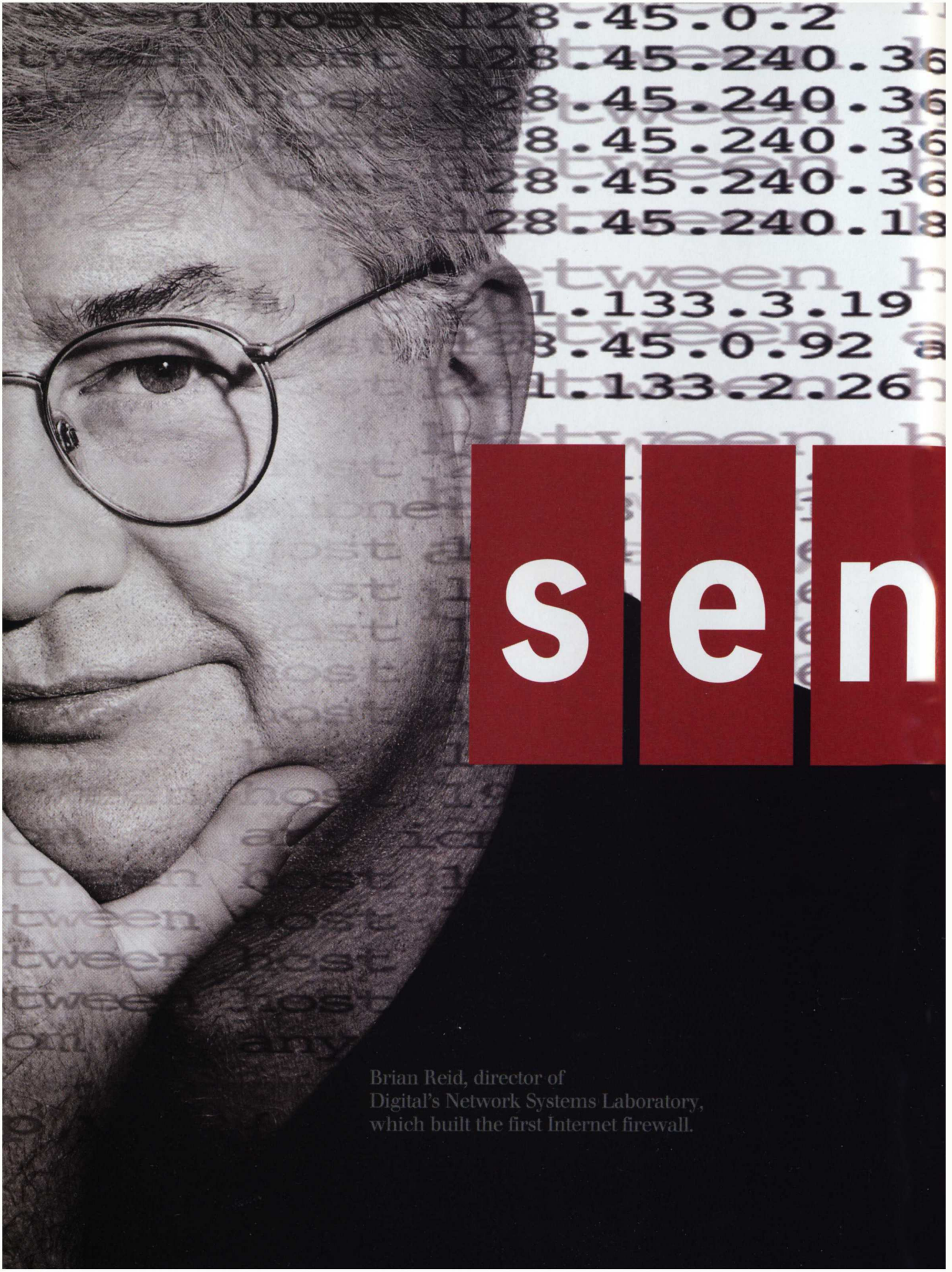
ANTIBIOTICS COME OUT OF THE SHADOWS

New Research Offers Hope of Overcoming Resistance

JAN/FEB 1998
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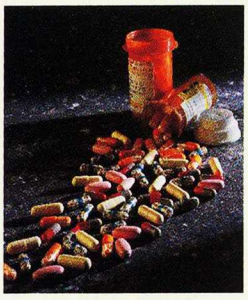


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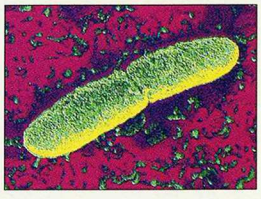


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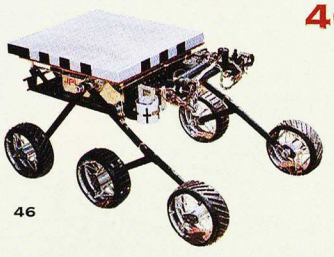


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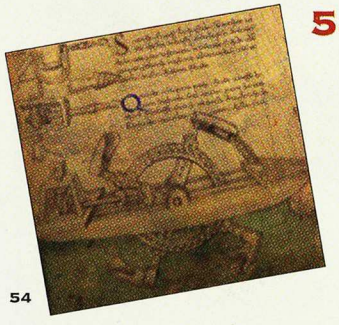


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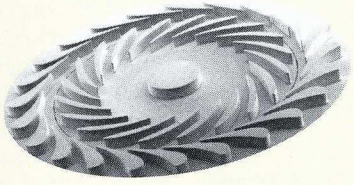
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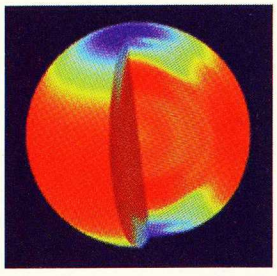
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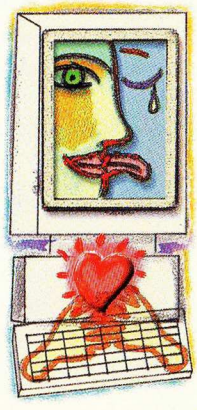
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First Line

MODULATING OUR FREQUENCY . . .

. . . so that we can lock on to yours in the year to come

JUST like a radio station, a magazine has a frequency. In our case, the frequency has been somewhat unusual: eight times per year. If you think about it, few other magazines publish on this schedule. We all know weeklies, (*Time*), monthlies (*The Atlantic*), quarterlies (*Paris Review*), and bimonthlies (*Civilization*). What is much less familiar is a magazine that comes out every six weeks and three days. And so, as of the issue you're holding, *MIT's Technology Review* is going to get in step with the rest of the publishing world. We are now a bimonthly publication, coming out regular as clockwork six times a year.

We realize that this change means we're going to be giving you two fewer issues per year. And, as demanding consumers, you will expect to receive added value to compensate for the reduction in frequency. You'll be getting it—in spades. As of the May/June issue, just two issues from now, *Technology Review* will be completely reinvented and relaunched as what is in essence a new publication. First of all, we'll have an entirely new graphic design that is cleaner, more contemporary, and more compelling than anything we've done yet. The new design is being carried out by the award-winning Art Director of *Civilization* magazine, David Herbick.

Along with our new Herbick design will go a shift in editorial focus. Although I don't want to give everything away yet, the new conceptual center of *Technology Review* will be innovation: the process by which humanity constantly upgrades its tools and techniques. This process is happening all over our society. In fact, in my view innovation is one of the distinguishing features of the society we live in—just as philosophy distinguished the ancient Greeks and artistic humanism the Italians of the Renaissance. Our society is a society of innovation, and the new *Technology Review* will analyze, interpret, and evaluate that process for our readers in every single issue.

Although innovation can be seen in almost every area of technology, it is happening particularly quickly in certain areas. Three that spring to mind are information technology, biotechnology, and materials science. (Indeed, Michael Dertouzos, director of the MIT Laboratory of Computer Science, refers to these three pacesetters as the "Three Queens.") In each of these fields, basic research is bleeding over with surprising speed into the commercial sector. Concepts that were the stuff of fundamental research a year ago are emerging as promising new ventures today; in six months they will be products. And as this process moves forward, lots of old boundary lines get crossed and then obliterated. Basic researchers, for example, become entrepreneurs. Corporate managers find themselves running cutting-edge research labs. Venture capitalists read *Nature* as intensely as they do the *Wall Street Journal*. Policymakers begin to think about undoing regulations rather than creating them.

The new *Technology Review* will go behind the scenes into all these areas where traditional boundary lines are disappearing as innovation proceeds. With the help of the very best professional writers in science and technology we will be bringing you vital information about how today's basic research becomes tomorrow's startup companies, about what corporate R&D strategies are really working—and which aren't, about who the innovators are (in universities and in companies), and what our society needs to do to keep the process of innovation moving ahead with accelerating speed. Our stories will focus strongly on the *people* who make all this happen, not just on the remarkable new technologies they create. Technology is, after all, one of the defining activities of our species, and the new *Technology Review* will be very interested in technology as an expression of our humanity.

One of the things that makes this new editorial focus appropriate for *Technology Review* is that MIT has never been a place where learning and practice were conceived of as separate functions. From its inception, "the Tech" has been a place where concept and application were seen as inextricably intertwined. One result of that philosophy has been that MIT is a hotbed of high-tech entrepreneurship. A recent study by BankBoston revealed that MIT alumni, alumnae, faculty, and students have founded 4,000 companies in the United States. In 1994, these companies employed 1.1 million people and generated $232 billion in worldwide sales. And while MIT has always been a fertile ground for startups, research universities in general are today a more critical part of the national innovation system than they have ever been.

Our revitalized magazine will therefore resonate with the mission of MIT. But it won't be a magazine solely about events in Cambridge. Far from it. As before, *Technology Review* will be a magazine with national reach and scope.

We're confident that our new editorial focus, presented in a striking new graphic package, will more than make up for the change in frequency. But, to make sure you're satisfied, we will also be sharply improving our World Wide Web site over the year to come. All in all, I think that the next year will be an exciting and (dare I say it?) "innovative" one both for us on Vassar Street in Cambridge, Mass., and for our readers around the United States and around the world.

As you see these changes making their way into our pages, please let us know how you think we're doing—what we're doing well and what we can do better. Our own process of growth and development depends on our being in tune with you. Staying on your frequency, as it were.■

JOHN BENDITT
EDITOR IN CHIEF

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Letters

CAN SATELLITE POWER SHINE?

Although a variety of factors played supporting roles, the primary reason that the Space Solar Power (SSP) systems discussed by Martin I. Hoffert and Seth D. Potter in "Beam It Down: How the New Satellites Can Power the World" (*TR October 1997*) failed in the public arena in the 1970s was its projected cost. The scale of the so-called Reference System Solar Power Satellite (SPS) at five gigawatts produced per satellite, coupled with the particularly massive infrastructure requirements of that design, resulted in a cost-to-first-power of more than $250 billion (in 1996 dollars).

NASA recently completed a "fresh look" study of SSP systems (April 1997) that suggests that basic technologies and systems concepts now exist that might make power from space far more economically feasible in the future—and amenable to strategies that are similar to those of the new telecommunications satellite constellations.

In particular, one of the strategies that is enabling the profitable deployment of large-scale communications satellite constellations is the modularization of architectures and resultant use of many identical satellites to create a single system. Other space systems or advanced hardware are the same in this regard: production in quantity can lead to dramatically lower costs per pound of equipment.

Economically viable SSP concepts will probably rely on similar technical strategies. In this regard at least, a strategic connection may exist between the new satellite systems and possible future SSP systems. However, the physics of efficient wireless power transmission dictates that even the smallest transmitter for that purpose will be orders of magnitude larger and more powerful than the largest satellite transmitter designed for communications purposes only. This disparity would make a modification of communications satellites to allow them to undertake wireless power transmission highly problematic. Perhaps a more likely path will be one that involves initial, relatively small-scale space solar-power systems (that still produce many megawatts) that augment their revenues by also providing communications services, rather than communications satellites that "grow" to become SPS.

JOHN C. MANKINS
NASA
Washington, D.C.

The authors underestimate a serious problem afflicting low-orbiting satellites, namely that they spend 18–36 percent of their time in the dark—where no solar energy is available. The authors dismiss this problem by stating, "At least one satellite will always be in view of the receiving station." However, the authors fail to acknowledge that this satellite may be in the dark!

This changes the problem from "Can a satellite receive solar energy and transmit microwave energy?" to "Can a satellite receive energy, store it in some kind of 'battery,' and transmit the power later?" The problems, costs, and perils of storing energy on earth are hard enough. But the problems of storing energy in space, where the weight of a "battery" is very expensive, seem insurmountable.

ROBERT A. PEASE
National Semiconductor Corp.
Santa Clara, Calif.

"Beam It Down" reminded me of the time in the 1970s when, as a PhD student of geology at Indiana University, I worked with NASA scientists on lunar soil samples. We debated the possibilities of mining the moon for the resources required to build power-producing satellites such as those mentioned in the article and were confident that we

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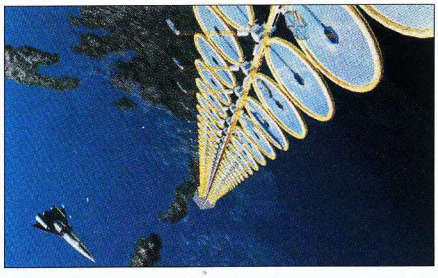
However, there was an obstacle that was likely to (and, I believe, did) doom the plan: defense of the system. Space-based power plants are extremely hard to defend against an enemy with even rudimentary launch capabilities, and earth-based rectennas are extremely susceptible to small missiles or bombs. Hoffert and Potter failed to address such vulnerability.

Although one might argue that communications satellites are also at risk, there are so many back-up facilities for communications, at least in the United States, that the loss of one or several of these satellites is not likely to upset day-to-day living drastically. It is easy to imagine the consequences, however, if even a small town lost its power supply for an extended time. In today's relatively calm political world, we would like to think that our technological endeavors do not need to address such concerns. Unfortunately, that is not the case.

CRAIG H. MOORE
Bloomington, Ind.

In order to advance their premise that low-orbiting satellites will be the only acceptable way of meeting the world's future electricity needs, the authors portray existing alternatives pessimistically. They claim that low-orbiting satellites will require far less land than terrestrial renewable sources, which would "compete with people, agriculture, and natural ecosystems were they the basis of a global energy system." The authors estimate that each square meter of rectenna "could yield as much as 100 watts of electricity," whereas ground-based photovoltaics produce "fewer than 10 watts of electricity per square meter." Actually, today's photovoltaic arrays produce more than twice that amount of electricity, resulting in a peak efficiency of 10 percent. By the time a satellite system becomes operational, photovoltaics will probably have a 30 percent efficiency rate, thereby bringing the land-use ratio down. Clearly, land requirement is not a very compelling argument, especially since much of the terrestrial photovoltaics could be installed on roofs and in deserts.

CHARLES J. SWET
Mt. Airy, Md.



The Authors Reply:

It is inevitable and healthy at this early phase that there be controversy over architectures and evolutionary paths of a new global energy source. Regardless of present disparities in size and power, we believe that low earth orbit (LEO) communications satellite infrastructures are a good starting-point for a space power industry.

While present low-altitude communication satellites have antennae only a few meters in diameter, a standard approach to increasing communication channels is creating nonoverlapping spot beams on the ground using a larger area of transmitting antennae. The drive to create more bandwidth is inexorable, and the trend in satellites is toward many independent beams emanating from platforms as large as hundreds of meters. Such antennae would be comparable in size to the phased array of the Sunsynchronous Sun Tower of the NASA Fresh Look Study designed to beam hundreds of megawatts of evening time electricity to the surface. Moreover, the NASA Fresh Look study has already identified an ingenious architecture for gradually increasing collected solar power in orbit by adding to modular strings of solar cells (independent of antenna size). Such strings automatically orient themselves vertically by gravity gradients, and could extend tens of kilometers upwards, as depicted on the October 1997 cover of *Technology Review*.

As Robert Pease observes, satellites in LEO are dark at times. However, the solution Pease proposes, massive battery storage, is a straw man. We envision computer-controlled relays beaming energy from satellites in the sun to those in the earth's shadow for retransmission to earth. With no atmosphere or rain, space is an excellent environment for efficient power beaming by high-frequency microwaves or even lasers.

While terrorists will always be tempted by energy sources, they may find it easier to strike against those based on earth. Compared with solar power satellites, whose interception requires sophisticated multistage rockets, terrestrial power plants can be taken out rather easily, perhaps by hand-held "stinger" missiles. However, should space-based satellites become a target, they could be fortified against attack.

If photovoltaic efficiency rises, it will do so for both space and ground-based applications. Therefore, the ratio of terrestrial-to-space-based power will remain roughly constant.

All energy sources have advantages and disadvantages. Space power is one of the precious few energy options permitting

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economic development while stabilizing CO_2 emissions. We cannot afford to lose the opportunity to research, develop, demonstrate, and commercialize it.

TOWARD A WORLD WITHOUT LANDMINES

Philip Morrison and Kosta Tsipis are to be commended for advocating technologies that can make real headway against landmines in "New Hope in the Minefields" (*TR October 1997*). The United States remains firmly committed to addressing the humanitarian crisis that landmines pose and leads the world in the effort to remove them. Since 1993, we have devoted more than $153 million to demining activities. In 1998, we plan to commit some $80 million for this purpose—roughly as much as the rest of the world, as Secretary of State Madeline Albright announced on October 31, when she unveiled the U.S. demining initiative to eliminate the landmine threat to civilians by the year 2010. U.S. experts have helped remove landmines in 15 nations, and we have trained and equipped as many as one-fourth of all the world's active deminers.



As the authors point out, the demining technologies now in use are slow and painfully inefficient. However, your readers should know that the United States leads the world in developing more effective demining technologies. Since 1995, the Department of Defense (DOD) has pursued an R&D program devoted to increasing the safety, speed, and efficiency of demining. The President accelerated these efforts in 1996 and directed that the resulting improved technologies be shared with the international community. The DOD's demining program, the sponsor of most of the systems described by Morrison and Tsipis, focuses on rapid prototyping of near-term, cost-effective solutions to specific demining problems. As of October 1997, it has developed and evaluated 68 prototype items.

DOD is exploring more far-reaching approaches as well. Under its Multidisciplinary University Research Initiative, three university consortia—led by Duke University, Northeastern University, and the University of Missouri at Rolla—are seeking innovative science-based approaches and advancing the basic understanding of mine detection, removal, and neutralization.

DOD has created a Center of Excellence in Unexploded Ordnance to coordinate technology development efforts across other military missions that share the need to detect and dispose of unexploded ordnance. In 1997, these other missions, including countermine warfare and explosive ordnance disposal, conducted $115 million worth of R&D in addition to the $14 million specifically devoted to humanitarian demining R&D. In October 1997, DOD established a Joint Unexploded Ordnance Coordinating Office to coordinate relevant DOD programs as well as those in other federal agencies such as the Department of Energy and the Federal Aviation Administration. This office will also work closely with industry, academia, and international organizations. Finally, the United States is working with international partners, both bilaterally and multilaterally, to develop mine detection and clearance technology.

As Morrison and Tsipis point out, the technical challenges posed by antipersonnel landmines are quite formidable, and no "silver bullet" solutions appear to be waiting on the horizon. Nevertheless, over the past three years, the United States has successfully developed a variety of useful technologies that have made the deminer's task more efficient and effective, as well as safer. We are committed to bringing still more effective demining technologies to fruition and sharing them with the world.

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MIT Reporter

AN INSIDE LOOK AT RESEARCH AT MIT

MICROMACHINERY

Shirt-Button Turbines



Researchers at MIT's Gas Turbine Laboratory, led by director Alan Epstein, constructed this 4-mm turbine wheel out of silicon as part of their effort to create a miniature turbine engine.

Look inside a laptop computer and you'll probably find that the largest and heaviest single component is the battery. Despite the remarkable progress scientists and engineers have made in shrinking the electronic and mechanical components inside portable PCs, battery technology has obstinately refused miniaturization. Now a research team at MIT's Gas Turbine Laboratory has embarked on an ambitious project to develop a turbine engine the size of a shirt button, linked to a tiny electric generator and capable of producing 10 to 20 times as much power as the best chemical batteries.

Spurred by a wave of interest in MEMS devices—microelectrical and mechanical systems fabricated like silicon chips—lab director Alan Epstein and his colleagues began investigating miniature turbines about four years ago. MIT's Lincoln Laboratory in Lexington, Mass., provided some seed money to start research on the topic, and the project eventually drew the interest of the U.S. Army Research Office, which in 1994 agreed to provide the group $5 to $6 million over five years in the hope that microturbines will provide portable power sources for individual soldiers.

Like a conventional jet engine, the miniature turbine will include three key components: a combustion chamber, a turbine wheel, and a compressor wheel. Fuel burning in the combustion chamber sends exhaust gases through the blades of the turbine wheel, causing it to rotate, which in turn drives the compressor wheel via a central shaft. The vaned compressor rotor then draws outside air into the chamber to feed the burning of more fuel.

One of the first questions the researchers sought to address was whether turbine technology could generate sufficient power at such a tiny scale. "The key to achieving high power density in rotating machinery is high peripheral speed," Epstein explains. Peripheral speed is the speed at which the outer rim of the turbine's vaned wheels turn. Spinning at 2.5 million revolutions per minute, the tiny wheels need to reach a peripheral speed of 300 to 600 meters per second—perhaps twice as fast as conventional turbine rotors. High peripheral speed in turn implies high peripheral stress: if the rotor's materials are not strong enough to withstand this stress, they will fracture.

Members of Epstein's team conducted a two-year scaling study to investigate the prospects for miniaturization. To their surprise, they found that many of the obstacles they anticipated did not materialize—and that miniaturization actually bestowed some advantages. "We felt initially that scaling effects were going to cause problems relating to the viscosity of the air," Epstein says. Viscous forces in the air are larger at microscales because air molecules are proportionally larger. A butterfly, for example, must expend proportionately greater energy overcoming air viscosity than a Boeing 747.

As it turned out, microscale air-viscosity effects were not great enough to require a substantially different design approach. In addition, team members realized that since microscale materials are likely to have fewer flaws than macroscale materials, they are proportionately stronger. As a result, the tiny rotors can actually be spun at higher speeds with a lower risk of fracture than conventional turbine rotors.

Armed with this information, the team began to develop and test the turbine's components. Last spring the researchers demonstrated the feasibility of a 2-millimeter-long combustion chamber and constructed a turbine wheel 4 millimeters in diameter out of silicon, using microfabrication techniques similar to those used to mass produce computer chips. They are now testing the low-friction air bearings that will permit the turbine wheel to spin at full speed. According to Epstein, the design of the third major component in the engine, the compressor wheel, will require only minor changes in the turbine wheel.

Over the next few months, the researchers plan to demonstrate the viability of a thin-film electric starter-generator,

PHOTO: MA SCHMIDT/CC LIN

to be mounted on a shroud over the compressor blades, and then embark on the next stage of their project: integrating the components onto a single silicon chip. Since the high-temperature performance of silicon is limited, the team is simultaneously investigating methods for manufacturing microturbines out of silicon carbide, a tougher, more temperature-resistant material.

Ultimately, the researchers hope to produce a prototype turbine power plant weighing less than one gram and generating 10 to 20 watts of electricity. If this high-risk effort proves successful, inexpensive miniature turbine generators could eventually be stamped out in large quantities like computer chips, Epstein says, and microturbines could become as ubiquitous in civilian life as batteries.

"It's a very difficult technology development problem," says James H. Smith, micromachine technology team leader at the U.S. Department of Energy's Sandia National Laboratory in Albuquerque, N.Mex., "but the MIT group knows more about this than anyone else and they are making excellent progress. If they can solve the problems, the impact would be tremendous."

—*John Drake*

PLASTICS

Bubbles by the Billions

If the classic 1960s film *The Graduate* were remade today, Benjamin might receive two words of advice instead of one: "microcellular plastics." These polymer materials, permeated by bubbles less than 50 microns in diameter, are tough, light, and can be made remarkably thin—features that suggest all kinds of uses. Now people just have to figure out which of them to realize first.

Microcellular plastics (MCPs) are the brainchild of Nam Suh, head of MIT's Mechanical Engineering Department, who invented the process for making them in 1979. The idea was triggered by a question posed during lunch by an Eastman Kodak executive who was trying to devise a way for his company to "reduce the amount of plastics used in their products, and thus reduce manufacturing costs, without sacrificing physical properties," Suh recalls. The savings could be substantial, given that foamed plastics are widely used for packaging, thermal insulation, cushioning, and disposable dishes, among other items. Suh quickly suggested introducing microscopic bubbles into the polymer in order to cut down on the amount of material used.

"Coming up with the idea was easy," he recalls. "The hard part was figuring out how to make it."

Assisted by several MIT students, Suh hit upon a technique that involved mixing gas with liquid plastic under high pressure and then suddenly lowering the pressure to form bubbles (also called voids or cells) that are distributed uniformly throughout the material. Suh's approach created much smaller, more densely packed bubbles than the conventional method

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of adding "impurity particles" to the polymer melt—particles that create discontinuities in the polymer, which in turn give rise to voids. "The number of voids you can make that way is limited by the fact that you cannot add too many impurities without ruining the original material," Suh explains. Furthermore, the voids in conventional foamed plastics are typically at least 200 microns in diameter.



Nam Suh, head of MIT's Mechanical Engineering Department, believes that many, if not most, conventional plastic products could be made of microcellular plastics, a tough, thin, light-weight material containing 10 billion bubbles per centimeter.

Suh patented his process in 1984, but suspended work on MCPs until 1988, when he returned to MIT after serving for four years as an assistant director at the National Science Foundation.

Suh argues that manufacturers of many, if not most, plastic products could save materials and money by using MCPs. Because the tiny voids are so densely packed (on the order of 10 billion cells per cubic centimeter), MCPs use far less material than conventional foamed plastics. Simply put, they contain a greater proportion of empty spaces. "We can cut material costs by 10 to 95 percent, depending on the application," Suh notes. "And by using less material overall, less energy is needed for manufacturing and there will be less waste to be disposed of, or recycled, later." In addition, MCPs are better able than conventional plastics to resist breakage, shattering, fatigue, and cold temperatures, according to Matt Pallaver, executive vice president of Trexel, Inc., a company formed in 1994 to develop commercial uses for the new materials. (Trexel is the successor to Axiomatics, a company founded by Suh in 1983 to make instrumentation for the plastics-processing industry.)

"A big area for us is developing new thin products—plastic foams that are as thin as paper," he says. These could be used, for example, as coatings for data communications wires. "You cannot use conventional foams for this because the cells themselves are bigger than the thing you're trying to make," he explains.

Trexel is now working with major plastics manufacturers to develop at least 18 different applications for the material. Trexel representatives are unable to discuss the details of these projects for proprietary reasons, but say the applications they are exploring include automotive parts, pipes, insulated housing for cables and wires, construction materials, containers (such as bottles and cans), and—at the low end—disposable plates and cups. "We're still trying to figure out new applications," Pallaver says.

"With new uses for plastics being discovered every day," adds Chul Park, a mechanical engineer at the University of Toronto who worked with Suh at MIT, "MCPs have more market potential than people can imagine."

—*Steve Nadis*

FIBEROPTICS

Telecommunications Seeks Its Guiding Light

"Pipe it in!" That's the battle cry in telecommunications these days. The more information that can travel down an optical fiber—whether as phone calls, video games, movies, or symphonies—the better. Now MIT researchers in materials science, physics, and electrical engineering and computer science have collaborated to create a device that could dramatically increase the carrying capacity of optical fibers. The device, a "photonic bandgap microcavity resonator," uses a microcavity, or defect, in a material called photonic crystal to guide the behavior of photons in much the same way that defects in a semiconductor can be used to control electrical properties.

The device comes at a crucial time, notes Lionel Kimerling, one of the project's supervisors and director of the Materials Processing Center at MIT. Telecommunications companies need to increase the carrying capacity, or bandwidth, of the fiber base already installed in just about all buildings. Since adding more fiber is costly, telecommunications companies are looking for ways to process signals more quickly—a task traditionally assigned to electronics. Although optical fibers can carry many data streams simultaneously, the signals must be processed sequentially—switching a single phone call entails processing the entire highway of signals to pick out the one needed. That inordinate amount of processing plunks a speed limit on the information highway, effectively limiting the carrying capacity of the fiber. But electronic switching and processing devices themselves are hitting a glass ceiling in their career: although transistors are getting smaller and smaller, there is a limit to how many can fit on a chip.

The best near-term solution, a technique called wavelength division multiplexing pioneered by Lucent Technologies, uses an optical device called a channel drop filter to separate light into color bands, or frequencies. This enables different data streams to be channeled along separate frequencies so that the signals can be processed simultaneously rather than in sequence. The Lucent technology, however,

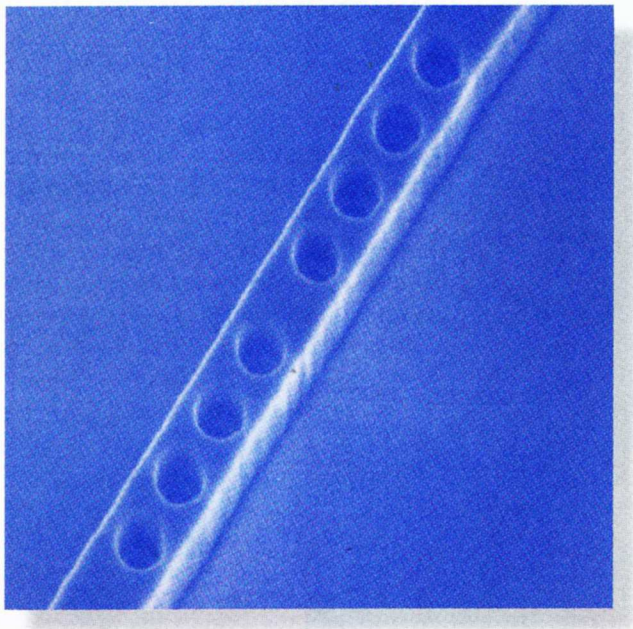
PHOTO: ALLAN DINES/NORTHSTAR PHOTOGRAPHY

has "a real estate problem," says graduate student Jim Foresi, who was involved in the fabrication and testing of the MIT device. Current designs are built on a centimeter scale, making precise fabrication difficult and expensive. The devices for 16-channel systems, for instance, are so large that only two of them fit on a 6-inch wafer. At this scale, says Foresi, systems with hundreds of channels would be impractical.

The MIT resonator, or waveguide, could pave the way toward wavelength multiplexing technology on the micron scale—a major advantage for large systems that contain thousands of devices. The device uses a different kind of "filter"—a photonic crystal—to tease out a single frequency from a strand of light. Each waveguide is only 0.5 microns in width; although each captures only one frequency, 100 of them would still be smaller than the Lucent guides. Working in synch, they could let 100 signals travel down the same optical fiber at the same time.

"We all knew this was possible," says Henri Benisty, research scientist at the Condensed Matter Physics Lab at the Ecole Polytechnique in Palaisseau, France. "The real tour de force was to make the guide small and still obtain fair optical confinement."

The four-year project began in the physics department, where professor John Joannopoulos and research scientist Pierre Villeneuve explored what Joannopoulos calls the "magical properties" of photonic crystals. These artificial materials exhibit behavior that can be tailored specifically to affect the flow of light. Each perfect crystal acts as a filter: it prohibits entry to a certain range of frequencies, creating what is called a photonic bandgap. If there is a defect in the crystal, however, photons in the prohibited frequencies will be drawn to it. By altering the shape of the defect, scientists can "tune" a crystal to isolate a particular frequency.



In this 0.5-micron photonic crystal waveguide, recently fabricated and tested by MIT researchers, the holes act as mirrors, reflecting unwanted frequencies, while a defect in the crystal allows only a selected frequency to enter.

"The crystal allows you to custom design electromagnetic states with specific properties. You can pick off just the wavelength you want," Villeneuve explains.

Together with Kimerling, the researchers began to explore the idea of creating a tiny photonic crystal waveguide operating at optical wavelengths (around 1.5 microns). Previously designed photonic bandgap devices operate at microwave wavelengths (1 to 100 millimeters) and are 100 times larger. The materials of choice for MIT's photonic waveguide—silicon and silicon dioxide—are unusual in comparison with those currently used, but their great advantage is ease of miniaturization. "We wanted the waveguides small and to be able to integrate well with the material that chips are made of," Kimerling explains.

The waveguide was fabricated using a technique called x-ray lithography, which has been used in chip fabrication but never before applied to photonic devices. It consists of a line of eight air holes arrayed on either side of a tiny microcavity in a layer of otherwise unblemished single-crystal silicon. The silicon is mounted on a layer of silicon dioxide and a silicon base. The closely spaced air holes act as mirrors: they reflect a very wide range of frequencies through a destructive interference effect. The defect, however, permits one frequency that would otherwise be reflected to enter through the first four holes. It becomes trapped in the microcavity for a brief period of time, then exits through the second group of four holes.

The MIT device is not yet ready to hit the market. And one of the things that has to be done before it gets there is to make the waveguide compatible with current technology while minimizing signal loss and power. "One challenge I see is to couple the fiber photons into the narrow guides," points out French researcher Benisty.

Nonetheless, researchers contend that these tiny devices could lead to new types of switches, frequency modulators, channel drop filters, low-threshold lasers, and light-emitting diodes—essential elements in telecommunications. Ultimately, says Foresi, "what we want is an integrated optics technology that is compatible in materials and dimensions with integrated circuit technology, so we can capture the strengths of both technologies at the same time."

—*Vivien Marx*

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PHOTO: JIM FORESI

Trends

INNOVATIONS FROM THE WORLD OF TECHNOLOGY

ASTRONOMY

Blueprint of a Star

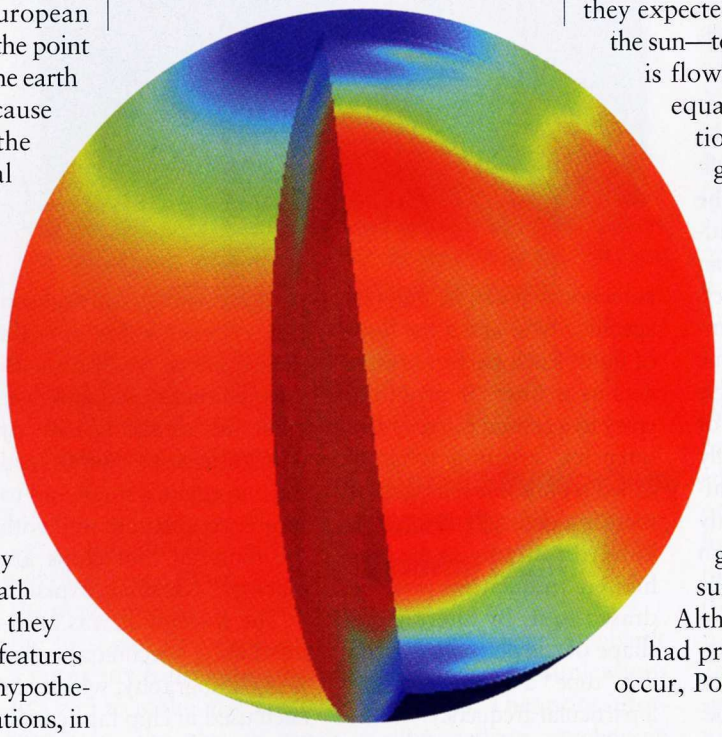
A million miles from the earth, the Solar and Heliospheric Observatory (SOHO) stares unblinking at the sun. Launched in December 1995 as a $1.2 billion joint mission of NASA and the European Space Agency, SOHO hangs at the point where the gravitational tugs of the earth and the sun are in balance. Because it orbits the sun in step with the earth, the observatory's visual and ultraviolet cameras and spectrometers monitor the star continuously. Now a crescendo of observations, gathered over the first two years of the mission, is leading scientists to a new understanding of the fusion-energy furnace whose light and warmth make life on earth possible.

Included among the data are findings that space scientists say are quite startling. Peering beneath the sun's blinding brilliance, they have observed for the first time features whose presence they had only hypothesized before. These new observations, in turn, are helping to solve at least one long-standing mystery: how the sun's corona is reheated.

Other solar-observing instruments orbit the earth (so the planet periodically blocks their view of the sun) or are earthbound and thus hampered by clouds and the atmosphere's absorption of ultraviolet and infrared radiation. SOHO's uninterrupted view and its array of advanced instruments have allowed scientists to observe previously unrecognized features of the sun's architecture. By measuring Doppler shifts in the light emanating from the sun, for example, scientists are able to analyze motions on the sun's surface and make inferences about its underlying structure, much as seismologists on earth measure activity on the planet's crust to learn about its interior.

"We're seeing what the internal structure of the sun is," says Arthur Poland of NASA's Goddard Space Flight Center, the space agency's chief scientist on the project. "It's giving us an understanding of how stars work. What we learn would be a blueprint for all stars."

Scientists have long known that the sun, like the earth, has an unmoving inner core and a rotating outer core 130,000 miles deep, known as the convection zone. Computer models had predicted turbulence in the convection zone. But now scientists are discovering that activity in the convection zone is even more complex than they had anticipated.



Helioseismology reveals that the sun's layers move at different speeds. Orange areas indicate average speeds, red areas are faster than average, yellow are slower than average, and blue slowest of all. The newly discovered jet stream current appears as a light blue oval surrounded by darker blue just under the surface of the polar region.

"What we see through helioseismology is a convection zone that is interesting and bizarre," says Richard Canfield, a physicist at Montana State University at Bozeman.

For example, scientists had previously observed movement of gases on the surface of the sun, but SOHO's data show that the currents run much deeper than they expected: the entire outer layer of the sun—to a depth of 15,000 miles—is flowing slowly from the solar equator to the poles. In addition, SOHO has discerned great "rivers" of gas circling beneath the poles in a pattern similar to the currents of the earth's jet stream. These were "a complete surprise," Poland notes.

In addition, SOHO's instruments have allowed scientists to witness shock waves rippling across the solar corona as gases explode above the sun's surface and fall back. Although some theoreticians had predicted these waves might occur, Poland says, they had never before been seen. "It was a 'Wow, that really does happen!'" he adds. "The theoretician might say, 'I told you so!'"

Scientists are also using SOHO to study the solar wind, the continuous stream of proton and electron particles that blow off the sun and flow through the solar system. Using a coronagraph to block the ball of the sun and sensitive digital cam-

PHOTO: NASA

eras equipped with charge-coupling devices to view its edges, they have discovered that powerful currents or eddies that emanate from the sun's equators play a more important role in distributing the solar wind than they had realized. And they have detected previously unknown elements in the solar wind, adding nickel, iron, silicon, sulfur, calcium and chromium to the list of 11 or so known elements.

"The quality of these telescopes is so good that you can actually watch material boiling off the sun in the solar wind," Canfield says.

SOHO appears to have solved one key riddle confronting researchers: how the solar corona gets so hot. The surface of the sun is 5,000 degrees Kelvin, yet the gaseous halo beyond, called the corona, reheats to 1 million degrees Kelvin. "A major question regarding the sun is why the corona is so hot," Canfield says.

The answer seems to lie in pancake-shaped regions of hydrogen and helium that Poland found moving upward through the sun. These pancakes arise from friction between the sun's inner core and its outer core. Their upward movement, he says, releases kinetic energy that is transformed into magnetic energy and radiates outward from the sun's surface.

Scientists had assumed that these regions of gas were spherical, like the bubbles formed in boiling water. Computer models based on this assumption, however, failed to explain the heating of the corona. The counterintuitive flat, oval shapes fit the model much better, Poland says, and their discovery may finally give scientists an accurate understanding of the process.

"We had no way of looking at these before," he adds. "It's like Galileo looking for the first time. We have to reconsider our view of how the sun works."

—*David Graham*

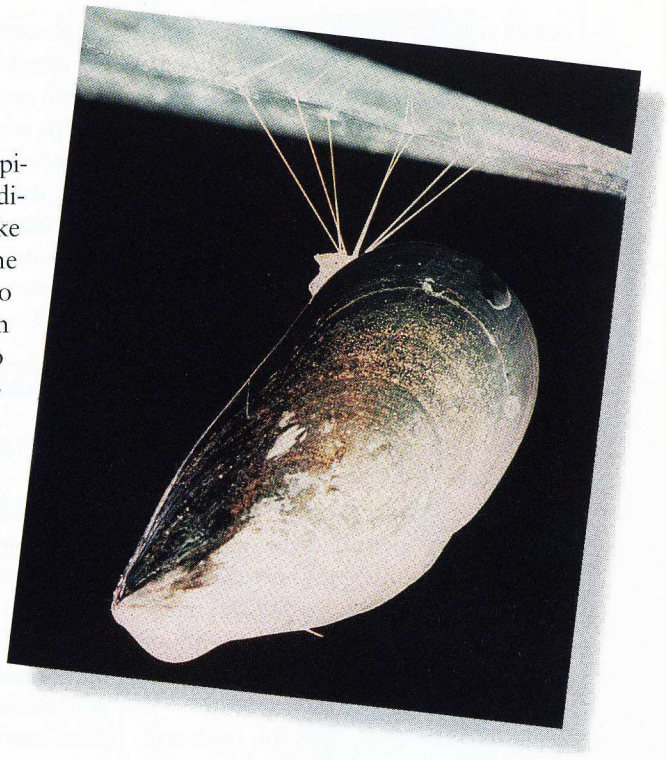


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BIOMATERIALS

Wonder Thread

Some natural materials, like spider silk, demonstrate extraordinary tensile strength; others, like elastins (proteins found in the tissue of vertebrates), are so resilient that they can stretch dramatically yet still return to their original size. Few materials, however, boast both properties—great strength and flexibility. That hasn't stopped materials scientists from looking for such substances, since these materials would be tremendously valuable in everything from artificial ligaments to tires. Now, in an unlikely place (the common marine mussel), researchers have found a threadlike substance that may fit the bill.



The tough, stretchy collagen threads produced by marine mussels serve as both a tether and a shock absorber. They are 5 times stronger and 16 times as resilient as human tendons, and may someday serve as the model for artificial ligaments.

J. Herbert Waite, a University of Delaware marine biochemist who is studying the mussel's so-called byssal threads, says he was drawn to the material in his quest to develop "artificial scaffolding" for use in repairing human tendons and ligaments. Materials strong enough to withstand the strain of a human joint often fail to bounce back to their original size. Waite compares them to the plastic used to hold a six-pack of aluminum cans together. "The material is tough," he says, "but when you pull that can out, it has no elastic recoil."

Mussels have long attracted the attention of marine biologists because of the super-strong adhesive they excrete at the end of their thread-like tethers to attach themselves to rocks, docks, and the underbellies of ships. But Waite says that equally impressive is the ability of the fine threads to hold the substantial mollusks while withstanding the constant motion of the tide.

Waite's graduate student and research team member Kathryn Coyne says that the byssal threads feature "a stiff tether" at the end closest to the organism and a "shock absorber" on its protruding end. What gives the byssal threads their remarkable mix of abilities, she explains, is the gradual transition from relative stiffness to relative elasticity along the length of the thread's core.

Close inspection of the molecular construction of byssal threads by Waite's team has revealed a seamless gradient between two types of collagen, a fibrous protein commonly found in bone, cartilage, and connective tissue. High concentrations of the stiffer collagen at the end of the thread closest to the mussel gradually give way to a similar but more elastic collagen, which rises to its peak concentration at the thread's far end.

According to Coyne, this is the first material known to combine proteins in such a manner. By using this technique in mussels, says Coyne, nature has cre-

PHOTO: J. HERBERT WAITE

ated a type of collagen (a tough material usually capable of stretching only 10 percent beyond its original length before breaking) that can stretch to 160 percent of its original length while still retaining an overall strength 5 times greater than a person's Achilles tendon.

Both the protein's molecular structure and the way the tendon-like material is seamlessly woven to achieve a gradient between stiffness and elasticity are of keen interest to materials designers. But Waite cautions that it is not yet feasible to manufacture materials featuring such gradual transitions from one type of protein to another. And so far the unique properties of the proteins in byssal threads offer no more than tantalizing clues about how uniform materials can be made more elastic without greatly diminishing their tensile strength.

Still, Waite adds, "it's fun to dream about versatile new materials, from steel-belted radials to shoe soles, that might draw upon byssal threads' secrets, being both soft and flexible yet tough enough to pound the pavement." At the very least, he says, the new findings "offer a completely new way of looking at the potential properties of structural collagen—the human body's most abundant protein."

—*Seth Shulman*

ACOUSTICS

The Anti-Music of the Aerospheres

Lots of powerful technologies have a serious drawback: they generate way too much noise. Consider the jet engine. We couldn't live without it, yet its noise can make life hellish for those in neighborhoods near airports. Researchers have long sought to improve methods of dampening the noise generated by jet engines, industrial equipment, automotive systems, even household products. Now it looks like aerospace engineers at Georgia Tech have found a promising candidate in an unlikely place: ceramic beads that were originally made for heat insulation.

With funding from NASA Langley Research Center, aerospace engineering professor Krishan Ahuja and doctoral student Richard Gaeta, Jr., built an acoustic liner they could wrap around noisy equipment to test the sound-dampening properties of the spheres. The researchers filled this shroud-like liner with beads—originally made from conventional ceramic powders for heat-insulation applications—that varied in diameter from 1 to 5 millimeters and featured multiple pin holes in their eggshell-thin walls.

Ahuja and Gaeta hypothesized that the loosely packed, perforated beads, known as aerospheres, would reduce noise by providing tortuous paths for the sound waves passing through. They also speculated that using spherical beads of varied sizes would absorb a broad range of sound frequencies.

They found that the aerospheres effectively blocked the noise generated by several types of jet nozzles that produce high-velocity, high-temperature air flow. In fact, the ceramic spheres absorbed both low and high frequencies at levels comparable to sound-absorbing materials such as acoustic foam and fiberglass. These materials, however, would burn or melt at the operating temperatures of these nozzles, which reach 1,000 degrees Fahrenheit. Other insulating materials such as ceramic wool and metallic honeycomb structures could survive extreme high temperatures, but are manufactured in preshaped forms, which would be difficult and costly to incorporate into many products. The beads, on the other hand, can readily be poured into almost any space.

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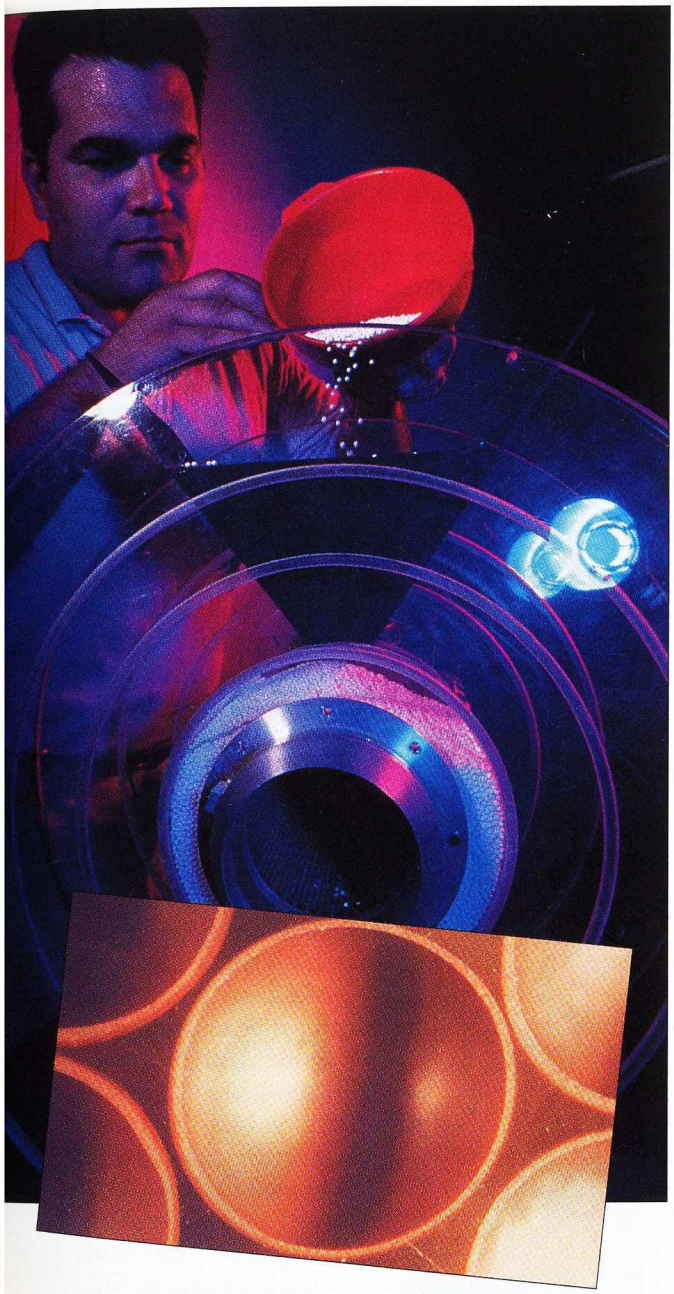
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Georgia Tech graduate student Richard Gaeta pours tiny, hollow spheres (inset) into a shroud that wraps around a jet exhaust to test their sound-absorbing qualities. The spheres are 3 mm in diameter and their walls are 0.01 mm thick.

the ceramic-bead liner could be particularly well suited for abating the earsplitting engine noise produced by the High-Speed Civil Transport (HSCT), which is now being developed in the United States to allow commercial air travel at supersonic speeds. The propulsion system of the HSCT relies on a nozzle that allows extremely efficient mixing of air and fuel at temperatures of 2,000 degrees Fahrenheit—but it also emits deafening noise over a wide range of frequencies.

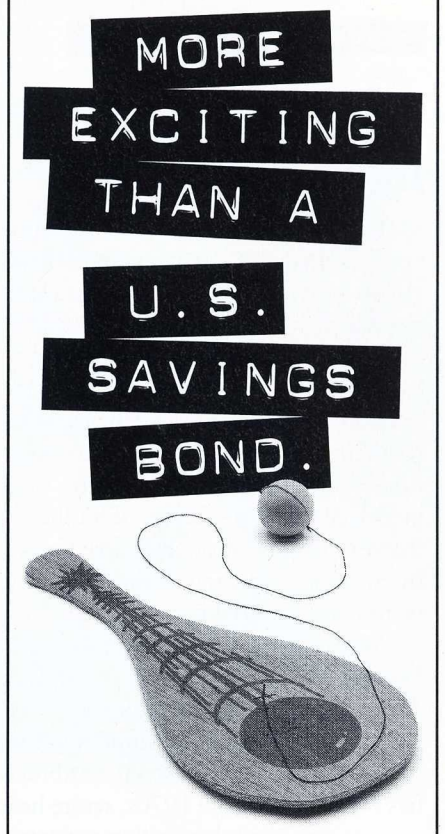
The cost of manufacturing ceramic-bead liners for jet aircraft noise absorption is not yet certain, says Joe K. Cochran, Jr., a professor of materials engineering at Georgia Tech and president of Ceramic Fillers, Inc. in Atlanta, which manufactured the aerospheres. But he adds that the performance benefits of the beads would outweigh their costs, at least for aerospace applications.

The ceramic beads may also prove useful as a noise absorber for industrial, automotive, and household equipment. For example, they could be poured into the bodies of pneumatic tools, automotive exhaust systems, and hair dryers after the products are molded.

The Georgia Tech researchers are also investigating the use of plastic spheres, which would be less expensive to produce than ceramic varieties. These could be useful in comparatively low-temperature applications, such as the walls in homes, hotels, and concert halls; certain compartments in aircraft and automobiles; and sound barriers in factories and along highways. It looks as though in the not-too-distant future, the spheres may be dampening many kinds of discordant music.

—*Mark Hodges*

PHOTOS: STANLEY LEARY/GEORGIA TECH



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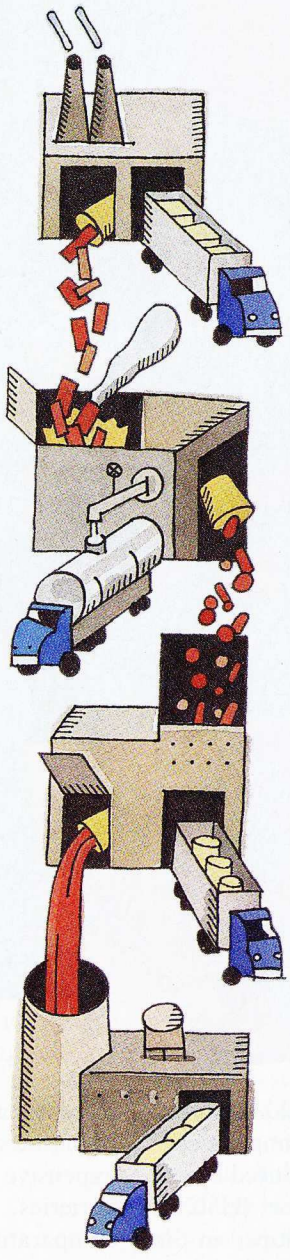
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INDUSTRIAL ECOLOGY

The Greening of Industrial Parks

In nature, organisms feed off one another's wastes, creating an endless, closed-loop system that recycles every particle of potentially useful material. In the United States, industry is trying to learn from nature's example. A growing number of government agencies, environmental organizations, and corporations are collaborating to create "eco-industrial parks"—clusters of businesses that reduce pollution and save money by feeding off each other's energy, water, and material byproducts.

The idea originated in Kalundborg, Denmark (see "A Down-to-Earth Approach to Clean Production," *TR* Feb/Mar 1996). At the Kalundborg site, where a complex industrial symbiosis has evolved since the 1970s, waste heat from a coal-burning power plant provides energy for a pharmaceutical company and warms more than 50 commercial fish ponds. The plant also sells the byproducts of combustion to other park tenants for use in manufacturing wallboard and concrete. The cyclical transfer of discarded energy and materials from one industry to another saves participating companies millions of dollars annually.



Since 1993, more than 20 U.S. cities from Oakland to Trenton have initiated plans to develop similar parks, many aiming to spur economic growth in low-income areas. They are assisted by an expanding network of industrial ecology consultants, such as Yale's Program in Industrial and Environmental Management, Cornell University's Work and Environment Initiative, and Indigo Development, an Oakland-based private consulting company. The concept is also gathering support from both government and industry: in October, the National Science Foundation and Lucent Technologies Foundation jointly awarded 18 grants totaling $1.2 million to support industrial ecology research across the country.

While most eco-industrial parks are still on the drawing board, a handful have begun to recruit tenants and set up operations. The 500-acre Port of Cape Charles Sustainable Technologies Industrial Park in Cape Charles, Va., the first of its kind to break ground in the United States, was designated by the President's Council on Sustainable Development in 1994 as one of four demonstration projects. The park opened in October 1996 with two anchor businesses. Four more tenants are lined up, and park organizers plan to open a multitenant building by the end of 1998. According to site manager Timothy Hayes, their aim is to attract companies that use "green" manufacturing technologies, creating an infrastructure that will allow tenants to reuse water, plastics, energy, and agricultural wastes. "Our goal is to set up an environment that facilitates these exchanges. Only the companies can make it happen," Hayes stresses.

Recognizing that many companies, even those whose managers are sympathetic to the idea of reducing waste, may be unwilling to relocate to an eco-industrial site, a second demonstration project is taking a regional approach. The 2200-acre Fairfield Ecological Industrial Park based in Fairfield, Md., near Baltimore, has established waste exchanges involving 160 companies both within and beyond the park borders. Rather than seeking out companies that already practice green manufacturing, explains site manager Michael Palumbo, the goal is to encourage businesses to make their practices more environmentally friendly.

Drawing on information from a Northeast regional waste-exchange network, Fairfield's managers identify

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high-value byproducts and contact companies that can pool these byproducts into batches large enough to sell. For example, low-grade oil runoff from storage and transport facilities is sold to asphalt producers or recycled for commercial use. Palumbo estimates that this runoff is worth $30 million annually. Companies at Fairfield are also testing the conversion of a nutrient byproduct into fertilizer pellets. Although the details are confidential, Palumbo says that one participating company produces 55 tons of the material per day. Currently, the company pays $1.75 million per year to dispose of it; the bulk of the money is spent on transporting it to landfills. By turning the byproduct into saleable fertilizer, "you're reducing your cost and replacing it with a revenue stream," he notes.

Perhaps the most intriguing option, however, is to bypass the concept of a site altogether and establish a "virtual" eco-industrial park—an approach now being pursued by a third demonstration project, the Brownsville-Matamoros Eco-Industrial Park in Brownsville, Tex. Although it entails higher transportation costs, this strategy avoids expensive land purchases, complex tenant interdependencies, and difficult relocations; as a result this approach may be easier to replicate. Using a computer model and database developed by the Bechtel Group, Inc., park planner Richard Luna is targeting about 30 companies within a 15-mile radius that could profitably participate in byproduct exchanges. "The main materials flows we've identified are cardboard, plastics, automotive products, oil, and solvents," he says.

"Companies don't realize that they have things that are marketable," notes John Ehrenfeld, director of the Technology, Business, and Environment Program at MIT. Advocates of eco-industrial parks hope that the potential economic benefits will lure more companies to participate. As Nicholas Gertler, an independent consultant on eco-park development, puts it, "Park planners can create a nice nest, but they need the birds."

—*Mark Dwortzan*

MARINE BIOLOGY

Fishing for Data

Ocean scientists searching for ways to preserve the nation's largest fisheries are turning to a previously untapped source of knowledge—the very fishermen who have depleted these fish stocks. In the process, they're hoping to make allies out of fishermen, whose livelihoods depend on the researchers' success.

In response to a growing fisheries crisis, in which dozens of the world's most valuable and popular seafoods are now endangered, marine scientists have established a novel research project called GLOBEC (Global Ocean Ecosystem Dynamics) to study how climate changes and other factors affect populations of marine organisms. The multi-year program funded by the National Science Foundation, the National Oceanic and Atmospheric Administration, and the National Marine Fisheries Service is focused on three sites: the northeast Pacific, the Antarctic region, and the Georges Bank fishery in the northwest Atlantic. Of these parallel efforts, the Georges Bank study is unique in its effort to draw commercial fishermen into the research process.



Woods Hole Oceanographic Institute biologist Peter Wiebe (right) and visiting scientist Erhan Mutlu adjust an acoustical device used to measure plankton density on Georges Bank as part of the Global Ocean Ecosystem Dynamics (GLOBEC) research project.

The potential partnership between scientists and fishermen has benefits for both sides. The researchers would get to take advantage of the fishing vessels; the fishing communities might learn about sustainable fishing practices, while participating in the global effort to save their jobs and their culture.

The immediate benefits will accrue to science. Researchers will need to take extensive samples of the waters at Georges Bank and adjacent regions and measure physical properties such as temperature, depth, and conductivity to see how populations of zooplankton, copepods (small marine crustaceans), and imperiled cod and haddock fluctuate in response to varying physical and biological conditions. "We need a tremendous amount of information, gathered over a broad area and many years, which is where the fishermen will come in," notes Peter Wiebe, a biologist at the Woods Hole Oceanographic Institute in Woods Hole, Mass., and a lead investigator in the Georges Bank project. "They're out in places we don't have the resources to get to, and it makes sense to enlist them," he says, either to collect data in the midst of a normal fishing run or to go out on special research trips.

"Fishermen are quite receptive to this

PHOTO: NANCY BAZILCHUK

opportunity," says Rollie Barnaby, himself a former fisherman who now works for the Sea Grant College Program at the University of New Hampshire (UNH). "Not only can they learn something and contribute to science, they can also earn a little extra money," he says, which would be most welcome to New England fishermen who have been hard hit by the collapse of local fisheries as a result of overfishing.

Craig Pendleton of Saco, Maine, is one fisherman eager to get involved in the project. Owing to government restrictions, Pendleton could fish for cod, haddock, and other so-called "groundfish" for only 88 days in 1997, leaving him plenty of time for research-related endeavors. He believes that fishing vessels and their crews could offer an economical means of collecting data at sea. "We have a lot of experience in the water and are used to operating as cheaply as possible," he says.

An equally important objective of the Georges Bank project is to improve relations between fishermen and researchers. "Fishermen need help understanding the biological reasons for the regulations they consider themselves to be 'inflicted' with," says biologist Ann Bucklin, director of the UNH Sea Grant Program. "The way to fix that problem is to get fishermen involved in the collection of the data that provide the basis for fishery management strategies and regulations."

Although 70 scientists are participating in the project, the fishermen component is quite small—limited, so far, to a single year of funding, which will cover Pendleton, his crew, and technical advisors for several research forays through the end of 1997. Bucklin proposes to develop a network of 3 to 10 fishing vessels to collect data. That could happen as early as 1998, but will require additional funding.

Assuming the pilot project is a success, "there may be some creative ways of financing this activity," Wiebe says. Apart from direct grants from the federal government, other options might include tax credits, contributions from the fish-processing industry, and extra fishing days granted to those taking part in the research effort.

Ultimately, Wiebe sees great potential for cooperative ventures of this nature. "A few years from now, the Georges Bank part of GLOBEC will be completed, but the need for this kind of information will still be here," he says. Moreover, just as sustainable fisheries have to be established, environmental monitoring also has to be done in a sustainable way, he adds. "The experience gained through GLOBEC may show us how to do that."

—*Steve Nadis*

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HEALTH & NUTRITION

Ruin Your Breath, Save Your Health: The Secret Life of Garlic and Onions



Researchers have long suspected that garlic's benefits extend beyond warding off vampires and bad dates. Now studies from several widely separated institutions have not only confirmed that garlic and its cousin the onion confer major health benefits—including such remarkable feats as fighting infection, cancer, and heart disease—but have also shown how they do it. And in the course of such studies, researchers may have come up with some important new therapeutic agents.

One study, led by microbiologist David Mirelman and biochemist Meir Wilchek of the Weizmann Institute of Science in Rehovot, Israel, found that allicin, a natural sulfur compound that protects garlic from soil parasites and fungi, effectively disables microbes that cause disease in humans. The team discovered that allicin blocks two groups of enzymes that normally empower infectious microbes to invade and survive in host tissue. Because both enzymes are found in a variety of bacteria, fungi, and viruses, allicin may prove to be a broad-spectrum antimicrobial drug. Moreover,



University of Wisconsin-Madison horticulture professor Irwin Goldman (center) watches as research assistant Kathryn Orvis prepares onions for a test-tube study of their role in preventing stroke and heart attack.

microbes are unlikely to develop resistance to allicin, Mirelman says, because to do so they would have to alter their own major enzymes, which would lead to their destruction.

One problem in using natural allicin as an antimicrobial drug is that it loses its beneficial properties within hours after a garlic clove is crushed and the compound begins reacting with other substances. The Weizmann researchers are therefore patenting a method to make synthetic allicin that can be stored for months without loss of effectiveness.

It seems as though infectious diseases aren't the only ones that garlic can ward off, either. In separate studies, nutritionist John Milner of Penn State's College of Health and Human Development discovered that garlic and onions can block the formation of nitrosamines in the test tube. Nitrosamines are potent cancer-causing chemicals that target the liver; Milner showed that the higher the dose of garlic and onions, the lower the levels of nitrosamines that formed in cells. These carcinogens, composed of nitrates and nitrites absorbed from food and water, build up naturally in the body. "Well over 90 percent of nitrosamines are carcinogens," he says, "so anything you can do to counteract them should be important in reducing cancer risk."

In another set of experiments, horticulturist Irwin Goldman of the University of Wisconsin in Madison found that the sulfur compounds that give garlic and onions their strong odor and flavor also prevent platelets (tiny disc-shaped bodies in blood) from sticking to each other in the test tube. "When someone has a blockage from plaque in an artery, platelets aggregate around the plaque to block blood flow," he says. Preventing the platelets from adhering to the plaque can reduce the risk of heart attack and stroke. And Goldman, who worked only with compounds extracted from onions, found that the more pungent the bulb, the more anti-stick capability it had.

But even if you choose the most pungent bulb possible for your cooking, you won't be getting the full therapeutic effect. The problem is that to reap the full benefits people would probably have to eat the onions raw because, as with allicin, these compounds quickly lose their potency. In fact, Goldman says, just one minute of cooking destroys all antiplatelet activity.

The solution, says Goldman, is to try to breed milder onions with high medicinal value that most people can tolerate raw. Instead of taking an aspirin a day to keep heart disease at bay, grocery stores may someday stock onions high in antiplatelet activity. "People are always looking for alternatives, especially from natural sources," he says. Now it looks as though some of those natural sources may be just what the doctor ordered—and the more pungent the better.

—*Carol Potera*

PHOTO: L. ROGER TURNER



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M I T C A E S

By Mary Knudson

The Hunt is *On*

For New Ways to Overcome Bacterial Resistance

JUST WHEN WE NEED A BREAK IN THE WORSENING WAR OF DRUG-RESISTANT MICROBES VERSUS ANTIBIOTICS, NEW TECHNOLOGIES ARE GALVANIZING THE PHARMACEUTICAL INDUSTRY INTO ACTION.

BACK in the 1980s, a false sense of security that infectious diseases were under control helped spur the drug industry to shift its resources away from creating new antibiotics. Since the discovery of penicillin, hailed in the '40s as the miracle drug, scientists had developed new generations of antibiotics that cured a wide range of diseases.

"There was a sense that the market and the clinical needs were already pretty well satisfied with existing agents," remembers Keith Bostian, who was a researcher at Merck Research Laboratory in the '80s. "The hurdle to qualify for a new drug candidate that could be competitive and take market share was getting higher and higher." As a result, many drug companies turned their basic research efforts to antiviral and antifungal medicines, few of which were on the market.



George H. Miller of the Schering-Plough Research Institute holds a petri dish containing a soil bacterium shown to have antibiotic activity nearly 20 years ago. Researchers have recently been developing a possible new kind of antibiotic from the organism.

What a difference a decade makes. Today Keith Bostian is the founding scientist and chief operating officer of Microcide Pharmaceuticals, Inc., a California company created in 1992 to develop novel antibiotics for serious infectious diseases. Bostian typifies the rejuvenated attitude of the pharmaceutical industry, which sees opportunities that didn't exist in the '80s to make and market new antibiotics as well as new types of bacterial killers. Across the country, researchers are competing furiously to uncover the private lives of bacteria, probing their genes to learn which are necessary for survival and which are involved in infecting people, and what mechanisms the microbes use to survive antibiotics. And pharmaceutical and biotech companies are nearly stampeding to find significant bacterial targets, create novel methods of attacking them, and be first to bring the new drugs to market.

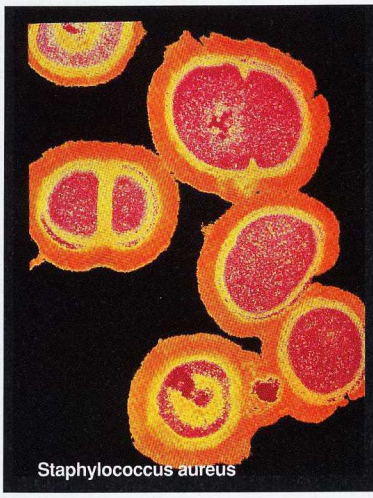
Photography by L. Barry Hetherington



The Seeds of Change

There isn't just one reason this rush is on. There are at least four motivators. Foremost is the growing sense of urgency to find ways to stem the advancing strains of bacteria no longer killed by major antibiotics. "Drug resistance is just an increasing problem in essentially every kind of bacterium that causes infection," says Michael Lancaster, section chief for antimicrobial resistance in the division of hospital infections at the U.S. Centers for Disease Control and Prevention (CDC). Among the diseases caused by drug-resistant bacteria are pneumonia, tuberculosis, ear infections, sexually transmitted diseases, diarrhea, and bloodstream and wound infections. "We are clearly in a public health crisis," says Stuart B. Levy, director of the Center for Adaptation Genetics and Drug Resistance at Tufts University School of Medicine, "and on the road to an impending public health disaster."

"Vancomycin-resistant enterococci (VRE) probably are the biggest resistance problem," says Lancaster. The VRE microbe, which can kill patients with weakened immune systems if it enters their bloodstreams, has been causing growing problems in hospitals. Among patients who got enterococci infections while in hospitals, the incidence of VRE rose from 0.3 percent in 1989 to 14.2 percent in 1996, according to the CDC. What makes VRE so significant is that vancomycin is not the first drug of choice to treat the microbe, but the last. Not only is VRE resistant to vancomycin, it is usually also resistant to all other drugs commonly used to treat it, says Lancaster. The fallback treatment is investigational drugs or high doses of combinations of drugs already on the market.


Staphylococcus aureus

Understanding which genes, and therefore which proteins, make a bacterium function is essential to learning how to fight it.

Microbiologists believe much antibiotic resistance is the result of natural selection. Resistant microbes tend to appear where an antibiotic is used frequently. As the bacteria reproduce, some mutations occur; eventually one bacterium is changed in a way that allows it to survive the drug. For instance, the mutant might have grown a thicker cell wall, making it impossible for the drug to permeate it. Or tiny cellular pumps that were used to get rid of waste products may acquire a new instruction that will now dump the antibiotic right out. This mutant, which can shield itself from the lethal drug, is the one that lives on.

Unfortunately for humans, mutating is not the only way bacteria develop antibiotic resistance. What scares public health officials even more is that bacteria can also transfer their genetic instructions for avoiding an antibiotic to other bacterial species. They have been most concerned that VRE will pass its high resistance to vancomycin over to a common and even more virulent and more aggressive bacterium, *Staphylococcus aureus*. That could be a huge problem because there are cases of staph bacteria that have proved resistant to every drug except vancomycin, Lancaster explains. Staph, which causes a range of problems from boils to pneumonia, toxic shock syndrome, and bloodstream infections, is the leading cause of infections patients get while they are in hospitals.

Last year a strain of staph that was moderately resistant to vancomycin showed up in Japan. This past August the CDC reported that for the first time in the United States a slightly different, moderately resistant strain had surfaced in Michigan. The CDC warned that this could be the harbinger of a fully resistant strain. Later, another moderately resistant strain showed up in New Jersey. The strains are all thought to be rare mutants. VRE has not yet passed its high resistance on to staph, but the watch is on.

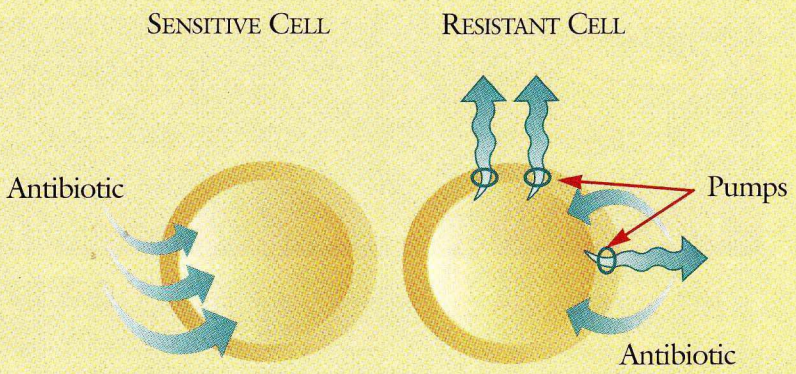
Drug-resistant bacteria are not confined to hospitals and nursing homes. In the last decade, says Alex Rakowsky, a medical officer for the Food and Drug Administration (FDA), health officials have learned that certain resistant bacteria occur more heavily in the suburbs, probably because affluent residents there take large numbers of antibiotics. Other pockets of highly resistant bacteria have been found in poor rural areas, for reasons not clear to health officials.

Learning Bacteria's Secrets

While doctors and public health officials were becoming aware of the extent of the drug-resistance problem, scientists and drug companies were taking note of the growing stockpile of knowledge pouring in from gene-sequencing projects. J. Craig Venter, chief executive officer of The Institute for Genomic Research in Rockville, Md., esti-

Mary Knudson, a science journalist based in Silver Spring, Md., covered medicine and science for The Baltimore Sun *for 18 years.*

THE BACTERIA DISPLAYED IN THE PHOTOGRAPHS ON THIS AND THE FOLLOWING PAGES HAVE EITHER SHOWN ANTIBIOTIC RESISTANCE OR COULD IN THE FUTURE, EXPERTS FEAR. PHOTO: PHOTO RESEARCHERS, INC./KARI LOUNATMAA



While antibiotics can enter and then destroy sensitive *Pseudomonas aeruginosa* cells, those that are resistant have hundreds of pumps that can bind to antibiotics and eject them.

mates that the biochemical codes for up to 40,000 new microbial genes already exist in public databases and that researchers will discover as many as 500,000 genes in the next decade, mostly in microbes. Now, says Venter, industry must winnow its interest to the few that will make the best drug targets.

Of particular interest to the pharmaceutical industry are the fully sequenced genomes already available for several bacteria. Understanding which genes, and therefore which proteins, make a bacterium function is essential to learning how to fight it. Having complete genomes "permits entirely new forms of analysis," says David Searls, a vice president at SmithKline Beecham Pharmaceuticals. "With a whole genome at your disposal, you have in a sense a closed world. You can analyze an organism in terms of biochemical pathways, for example, and be assured that you're going to have represented in your database every possible biochemical reaction." And that is why gene sequencing became the second motivator for drug makers to develop new antibiotics and rescue those in distress on the market.

Last summer at a forum on resistant bacteria held by the National Academy of Science's Institute of Medicine, gene sequencing pioneer Venter described data released from four of the first completely sequenced genomes of bacteria. Then he told his colleagues: "The chief breakthrough that allowed this to take place was not molecular biology. It was actually bioinformatics that allowed us to deal with thousands and thousands of sequences."

In August 1987 no one had heard of bioinformatics. Ten years later an Internet search engine came up with more than 22,000 references to it. This field of study was born when scientists began to realize that the volumes of data to come from gene sequencing would be of little use unless a systematic process could be devised to organize and analyze them. Using computer programs, researchers can compare sequences of newly discovered genes with known ones from other species. To experts, a close match may offer clues to the functions of the "new" genes. Genes that code for proteins are the target of much gene sequencing. Scientists can also use bioinformatics to determine "where and when the specific messages coding for these proteins are made," explains George S. Michaels, one of the early bioinformatics specialists.

And so this tool quickly became the third factor prompting the drug industry's renewed research interest in antibiotics. Almost overnight, bioinformatics is becoming a profession. Michaels, who now heads George Mason University's graduate program in bioinformatics, says his four-year-old program awarded its first Ph.D. last year. And in recognition of the importance the technology plays at SmithKline, last year that company named David Searls vice president for bioinformatics. "I think that genomic sequencing and bioinformatics opened up really unparalleled opportunities in antimicrobial research," says George H. Miller, presidential fellow-vice president for microbiology at the Schering-Plough Research Institute. "You can select new targets now."

Given the resistance problem and the new tools to try to do something about it, "there's a lot more enthusiasm" to create new antibiotics, says Allan Weinstein, vice president for international medical and regulatory affairs at Eli Lilly and Company. "You can look at current antibiotic therapy as sort of a sledgehammer," he explains, while the new approach "directed at specific genes necessary for bacterial life would be more of a stiletto."

The fourth factor behind the enthusiasm to search for new antibacterial drugs involves two other new tools that have been developed in the last 5 to 10 years that serve to speed up the hunt. In the past, chemists randomly prepared compounds one at a time to see if they had any usefulness as a drug. Now, explains Ted McDonald, director of chemistry at Pharmacopia, Inc., in Princeton, N.J., most drug companies have replaced that method with a much faster one. Through a process called combinatorial chemistry, pharmaceutical chemists create collections of small organic compounds in which they systematically vary the different units or building blocks in the compound's molecular structure, preparing many possible combinations.

Another technology called high-throughput screening allows these synthetic molecules to be screened in large groups. In one method, plates of 96 miniature wells containing a molecule and a protein target from a bacterium are passed over a detector that shows a color change when a

DIAGRAM: DEBORAH PERUGI, BASED ON MICROCIDE PHARMACEUTICALS GRAPHIC



Examples of Current R&D Efforts for Fighting Bacteria

Type	Compound	Company
New Antibiotics	Ziracin (an everninomicin)	Schering-Plough Research Institute
	Linezolid	Pharmacia & Upjohn
Antibiotic-resistance Disablers	Pump inhibitor, for use with fluoroquinolone antibiotics	Microcide Pharmaceuticals and Daiichi Pharmaceutical Co. collaboration
	"Methicillin potentiator," for use with beta-lactam antibiotics	Microcide Pharmaceuticals and Johnson & Johnson collaboration
Preventive Vaccines	Two pneumococcal conjugate vaccines	Wyeth-Lederle Vaccines and Pediatrics; also Pasteur Mérieux Connaught
	Vaccines against Lyme disease: Lymerix	SmithKline Beecham
	ImuLyme	Pasteur Mérieux Connaught
Phage	Several long-circulating variants against VREf strains	Exponential Biotherapies

molecule binds to a protein. Some companies prefer attaching molecules to polystyrene beads because of the ease of purifying the product after several chemical reactions by simply washing reagents and byproducts off the beads. Whatever method is employed, the bottom line for drug makers is speed. In the time it used to take to screen a few hundred compounds for potential drug activity, pharmaceutical companies now can screen tens of thousands.

Everybody's Responsibility

As one antibiotic after another loses ground to a new resistant strain of bacteria, government officials and scientists from industry, academia, and professional scientific and medical organizations have met to examine the problem and discuss what can be done. New alliances and partnerships are forming among public health departments and scientists based at universities, and between giant pharmaceutical companies and small biotechnology firms. Now the question is: Can we beat antibiotic resistance?

The answer involves almost everybody. Drug manufacturers are one significant part of the solution.

Pharmaceutical and biotech firms are placing in the pipeline many potential new drugs intended to help meet the challenge of resistant bacteria. One is a class of antibiotics known as everninomicin that the Schering-Plough Research Institute is developing. George Miller is glad his company hung on to a soil organism called *Micromonspora carbonacea*, which was shown to have antibiotic activity nearly 20 years ago. From 1979 to 1984 company researchers worked with the organism and found it could make an antibiotic that was not toxic and was active against a range of disease-causing microbes known as gram-positive bacteria. But the scientists quit working on it, Miller says, because in the '80s there was no need for a new antibiotic of this type.

In 1990, when they noticed that some gram-positive bacteria were beginning to develop resistance to existing drugs, Schering-Plough scientists plucked the organism from its home in the freezer and started back to work on it. Everninomicin contains seven different sugars that are not involved in any class of medicine used in people, Miller says. This means that no current form of drug resistance can transfer to the new antibiotic, which in lab and animal studies has killed resistant strains of staphylococci, streptococci, and enterococci, three of the most problematic bacteria. Miller points out, however, that "resistance will probably happen to all new drugs eventually."

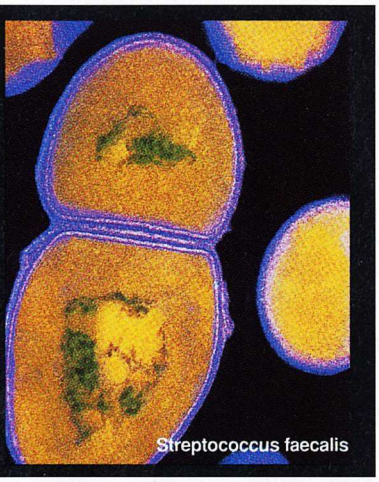
Clinical trials of the first everninomicin drug have begun in South Africa and Latin America. And they may start soon in the United States, Miller says. If those trials succeed, the FDA may take another two to three years to approve the drug, he adds.

Even sooner than that, another new class of antibiotics—the oxazolidinones—may be ready for use, courtesy of Pharmacia & Upjohn, Inc. Scientists at E. I. Du Pont de Nemours actually discovered oxazolidinones more than 10 years ago

but couldn't overcome a toxicity problem with the compound, so they stopped trying to develop it into a usable antibiotic. Gary Zurenko, a senior research scientist at Pharmacia & Upjohn, was sitting in a scientific meeting in New York in 1987 when Du Pont researchers described the product. Zurenko was intrigued by its unique mechanism of action, which unlike other inhibitors stops the initiation of protein synthesis in bacteria. This was significant because its way of preventing protein synthesis in bacteria implied that "organisms resistant to the known protein-synthesis inhibitors would likely not be resistant to the oxazolidinones," Zurenko explains. The compound also looked attractive as a drug candidate because it could be given by mouth as well as intravenously.

Over time, Pharmacia & Upjohn researchers developed a set of oxazolidinones far less toxic than the Du Pont compound. Zurenko reports that the first drug his group created, Linezolid, works against methicillin-resistant staphylococci, vancomycin-resistant enterococci, and penicillin-resistant streptococci and retains other key features of the early oxazolidinones. His company is now testing Linezolid on patients at several sites around the world, including in the United States.

One way to renew antibiotics' usefulness is to design drugs that disable resistance mechanisms in bacteria.



Resisting Resistance

Another new way to attack antimicrobial resistance is to design drugs that disable the antibiotic-resistance mechanisms in bacteria. Patients would take these drugs along with antibiotics already on the market, making them effective again. For instance, Microcide Pharmaceuticals, the antibacterial company begun in 1992, is focusing on this approach against four organisms—staphylococci, enterococci, pseudomonas, and streptococci—which together account for 44 percent of the 2 million infections that occur each year in U.S. hospitals.

One resistance mechanism Microcide is concerned with is the elaborate method *Pseudomonas aeruginosa* has developed to resist many antibiotics. This bacterium causes a variety of diseases, including pneumonia and infections of the skin, urinary tract, and bloodstream. The resistant microbe has evolved in such a way that it has hundreds of pumps that bind to antibiotics as they enter the bacterial cell. The pumps literally eject the medicine from the cell. Each bacterium can have as many as four variations of the basic pump.

To target and disable the pumps, the researchers first had to thoroughly understand the pumps' molecular biology. The investigators learned that often the pumps "recognize more than one type of antibiotic," says Keith Bostian, Microcide's founding scientist. "Some pumps recognize all the antibiotics." A crucial factor therefore became making sure that the inhibitor Microcide was developing would inactivate all four pumps.

This past fall Microcide screened and tested a variety of chemicals that inactivate the pumps. Bostian says the company is close to picking its best candidate for drug development and that clinical trials might occur next year, with the product possibly on the market three to four years later.

These are just a few examples of the potential new drugs many pharmaceutical companies are hoping will get to market and prove successful in holding the line against antibiotic-resistant bacteria. But just how much help the public can expect and how soon is hard to predict. "I couldn't honestly say whether I'm optimistic or not that they are going to fill the gap in time," says Joshua Lederberg, who chairs the Institute of Medicine's Forum on Emerging Infections and is a Nobel laureate. Because details of companies' work are private, he says "there is no way to gauge how far along they are."

Meanwhile, one approach to controlling infectious diseases that has been underutilized, Lederberg says, is preventive vaccines. He points to the success of the vaccine against *Haemophilus influenzae* type *b* (Hib). While the microbe sounds as if it causes the flu, it actually was the leading cause of meningitis, a potentially deadly disease, in U.S. infants during the 1980s. It also causes blood poisoning and pneumonia. Claire Broome, deputy director of the CDC, notes that the number of U.S. Hib cases in the '80s was on the same order of magnitude as polio cases before the polio vaccine. Now, she says, "The [Hib] vaccine has almost entirely wiped out Hib meningitis."

At least two drug companies are developing another bacterial vaccine, this one against pneumococcus, the leading cause of pneumonia and meningitis for all age groups in the United States and the most common bacterial cause of otitis media, middle-ear infections in children. Ear infections

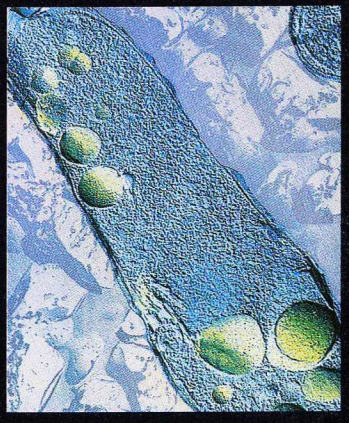
PHOTO: PHOTO RESEARCHERS, INC/CNRI

are a major reason for office visits to pediatricians, the prime cause of emergency-room visits for kids, and a common reason doctors pass out antibiotics. "If this vaccine is successful in preventing otitis media, that would be a tremendous step forward," says Broome.

Back to the Future

While most of the attention and competition is focused on creating new antibiotics and rescuing those now on the market, a few researchers advocate returning to the anti-infection remedies used before the introduction of antibiotics in the 1940s. One such treatment is bacteriophage. Commonly known as phage, this is a virus that grows in bacteria until it finally pops out and kills its host.

Phage treatments used in the '20s and '30s often failed. At the time scientists didn't understand that each kind of phage is highly specific; only one type will attack a particular species—and even strain—of bacteria. Reports of the treatment in journals were lacking in controls and filled with anecdotes, and many scientists looking at the studies today say they are not professionally acceptable.



Pseudomonas aeruginosa

Vaccines are an underutilized approach to controlling infectious diseases.

But Carl R. Merril, chief of the Laboratory of Biochemical Genetics at the National Institute of Mental Health, is enthusiastic about the potential for using phage therapy to treat serious infectious diseases in humans. Merril, who reported in the April 1996 *Proceedings of the National Academy of Sciences* (*PNAS*) that he had successfully used phage therapy in mice, says several procedures must be followed for phage treatments in people to be successful. First, the bacterium causing the infection must be cultured to determine the exact type and strain. Next, the strain has to be tested against different phage to find the one phage specific to that strain. Then a mutant phage must be grown in a manner that ensures that the patient's body will not see the virus as foreign and remove it. Finally the phage needs to be purified to eliminate any toxic bacterial fragments left after bursting free of its bacterial host. Merril says he has found that spinning phage in a centrifuge separates out bacterial particles.

Merril is collaborating with Exponential Biotherapies, a start-up biotech firm in New York, to develop phage therapies for use in people with major infectious diseases. Richard Carlton, a psychiatrist, founded the firm after meeting Merril and becoming impressed with his work. Carlton says that the first therapy the company hopes to market aims to kill a strain of vancomycin-resistant enterococcus called VREf, which causes skin, bloodstream, wound, and heart-valve infections.

At least one other American company reports that it is pursuing phage treatments. Formed in the fall of 1996, Phage Therapeutics is trying first to develop a treatment against resistant *Staphylococcus aureus*, according to Richard Honour, a microbiologist and the company's president and chief executive officer.

Because of the lack of rigorous scientific proof that phage treatment works against infectious diseases, the companies hoping to market it in the United States have taken on a big selling job.

Last November, Elizabeth Kutter, a biophysics professor, visited the Eliava Institute of Bacteriophage, Microbiology, and Virology in Tbilisi in the Republic of Georgia, where phage therapy is heavily used. She says the institute's clinicians most often administer phage treatment topically to treat wounds and burns, or orally for intestinal disorders and some other infections. "What I've seen is enough good data to make me think it's definitely worth further exploration," says Kutter, of Evergreen State College in Olympia, Wash.

Honour, whose company has a relationship with the Eliava Institute, says the work of researchers and doctors in Tbilisi and other parts of eastern Europe is not readily transferable to the United States. "They've saved thousands of lives, but you could never take those products or techniques and submit them to Western regulators," he says. When a treatment "works, it works well, but when it doesn't work, they don't know why."

Other Western experts are even more skeptical. Bruce Levin, a population and evolutionary biologist at Emory University who has conducted some successful animal experiments with phage therapy, says its main drawback for human use is its specificity. Identifying the particular species and strain of an infecting bacterium before treating patients could be a problem, he suggests. Also, he says, researchers have not yet proven that phage treatment works throughout the body. But despite his skepticism, Levin says that given the potential crisis antibiotic-resistant bacteria could cause, researchers should examine phage therapy in light of modern scientific knowledge.

PHOTO: PHOTO RESEARCHERS, INC/TONY BRAIN

Attacking on Other Fronts

Regardless of what treatments may be used once bacteria have infected people, scientists and public health officials agree that one crucial step in developing an effective offense against the microbes must be the establishment of a strong surveillance system. The system should pinpoint resistance problems early, give clues as to why they are happening, and quickly provide critical information to public health officials worldwide. But no worldwide system is in place, and surveillance in the United States is uneven and has major problems, according to public health officials themselves.

Rosamund Williams, a bacteriologist who is coordinating the new Antimicrobial Resistance Monitoring Program for the World Health Organization (WHO), spoke openly at last summer's Institute of Medicine forum about the outcome of the current lack of such a setup. "We know that we have a big problem with resistance to antimicrobial agents, but we don't know how big it is," she said. WHO is therefore starting a system that will attempt to strengthen the ability of laboratories within its 191 member countries to monitor resistance problems, build national reporting operations, and provide international coordination.

Even U.S. surveillance is spotty, David Bell, assistant to the director of the CDC's National Center for Infectious Diseases, pointed out during the meeting. The CDC has several systems that collect different information from various sources. The systems monitor hospital-acquired infections, pathogens in food, tuberculosis, sexually transmitted diseases, malaria, and others. Managed-care organizations also run private surveillance systems, while networks of universities—with funding largely from the drug industry—oversee others. "One of the problems we have," Bell said, "is that virtually none of these systems provides anywhere close to nationwide coverage."

There are other problems, too. "We really need to know more than which drugs are becoming resistant to which bugs," Bell said. "We need to know who are these patients with the resistant infections, and are they randomly distributed across a population group or do they fall into certain risk groups—for example, hospital patients, or people who travel abroad, or people who use a lot of antibiotics."

Fred Tenover, chief of the CDC's hospital-infections laboratory branch, said the resistance problem could be much worse than is already known because not all organisms are tested for resistance and some labs rely on improper testing methods. In one case last year, he said, 30 percent of the 2,100 labs looking for resistance in *Streptococcus pneumoniae* used the wrong test.

Effective treatments and strong surveillance systems that spread early warnings about resistant bacteria are still only part of a solution to fight drug-resistant bacteria. Public-health officials, doctors, and members of the drug industry also agree that preventing overuse of antibiotics is critical. "The more and more we use these antibiotics, the more selection we have, and these mutants will emerge," says Stuart Levy, president-elect of the American Society for Microbiology. "There is inadequate physician, veterinarian, farmer, and patient education," says Mitchell L. Cohen, director of the CDC's division of bacterial and mycotic diseases. He says doctors admit to overusing antibiotics by 15 to 20 percent.

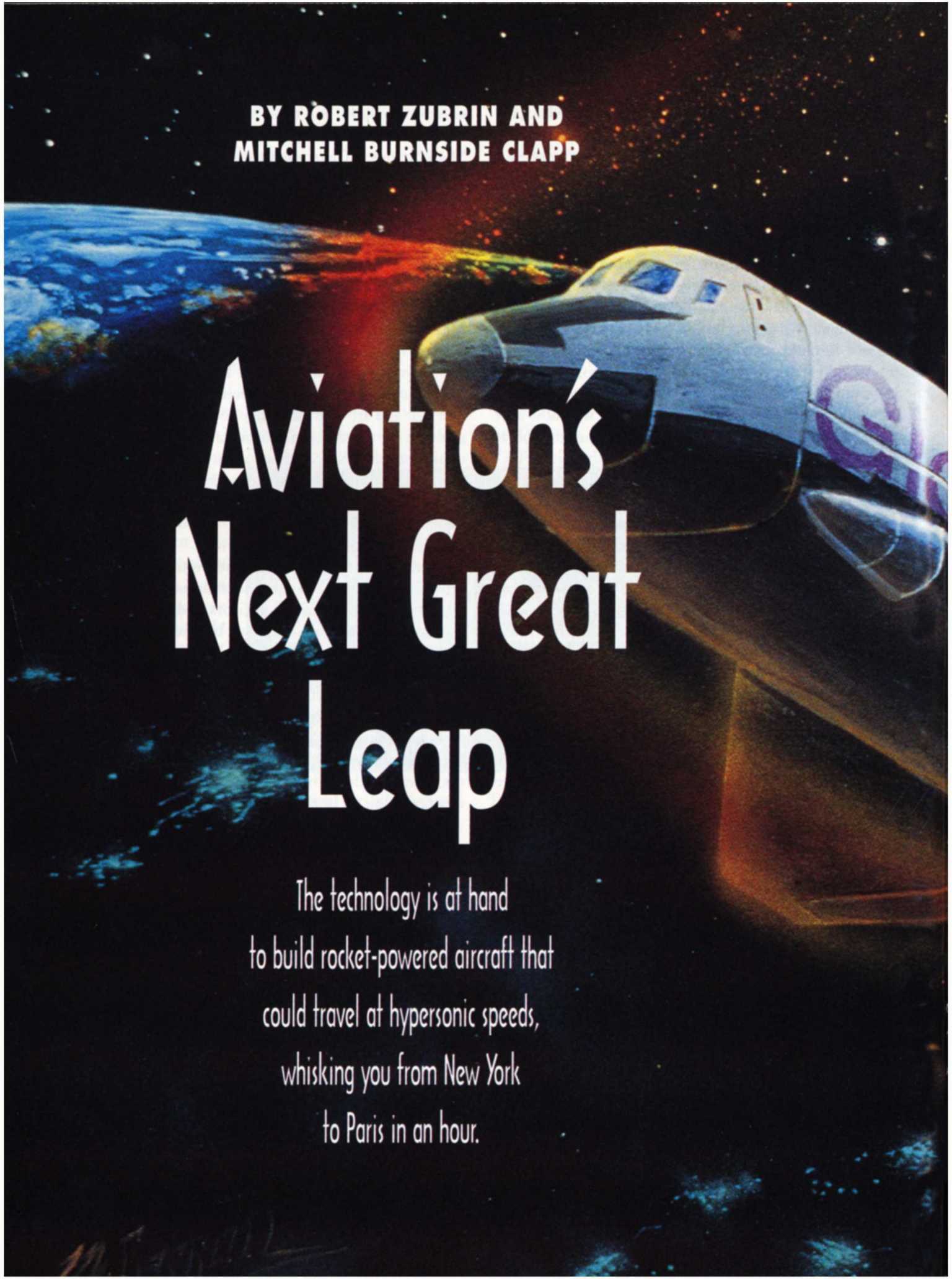
Doctors in managed-care settings, where pressures can mount to see high numbers of patients quickly, are among those who often over-prescribe antibiotics, says S. Michael Marcy, a Kaiser Foundation staff pediatrician and pediatrics professor at the University of Southern California and University of California at Los Angeles Schools of Medicine. Patients who don't receive an antibiotic on the first visit and are convinced they need one often return—a problem for doctors at managed-care facilities that try to reduce return visits, according to Marcy. Patient satisfaction surveys also contribute to generous prescriptions for antibiotics: "Now, up to 30 percent of our salary will be determined by our satisfaction rating," he says. The message becomes: give patients "what they want."

In answer to the criticism of antibiotic overuse, some professional medical and scientific organizations have begun distributing brochures for patients and doctors on the proper use of antibiotics. "It would be much more powerful and effective," urges Frederick Sparling, chair of the department of medicine at the University of North Carolina and president of the Infectious Diseases Society of America, if major professional organizations would all get behind one set of guidelines.

In the end, so many players exist in the saga of resistant microbes and their invasion of people that answering the question "Can we beat antibiotic resistance?" is impossible.

If scientists reveal the inner workings of all virulent microbes and design novel ways to overcome their drug resistance; doctors quit over-prescribing antibiotics and patients learn proper respect for the drugs; hospitals, nursing homes, and doctors' offices adhere to strict infection-control policies; and a strong global surveillance system is established; then humans would seem to have the advantage.

Except that bacteria have a much longer track record at adapting and surviving than humans. And scientists, left to wonder what unknown paths of mutations lie ahead, say they aren't willing to bet against the microbes. "I don't think any of us will ever develop an agent [for which it is] totally impossible to have resistance," says Zurenko of Pharmacia & Upjohn. "There are still a lot of imponderables," points out Joshua Lederberg. Yet based on the recent level of activity in antibiotic-resistance research, he says, "At least some of the right people are paying close attention. That was not true a couple of years ago." That, he says, is "progress."■



BY ROBERT ZUBRIN AND
MITCHELL BURNSIDE CLAPP

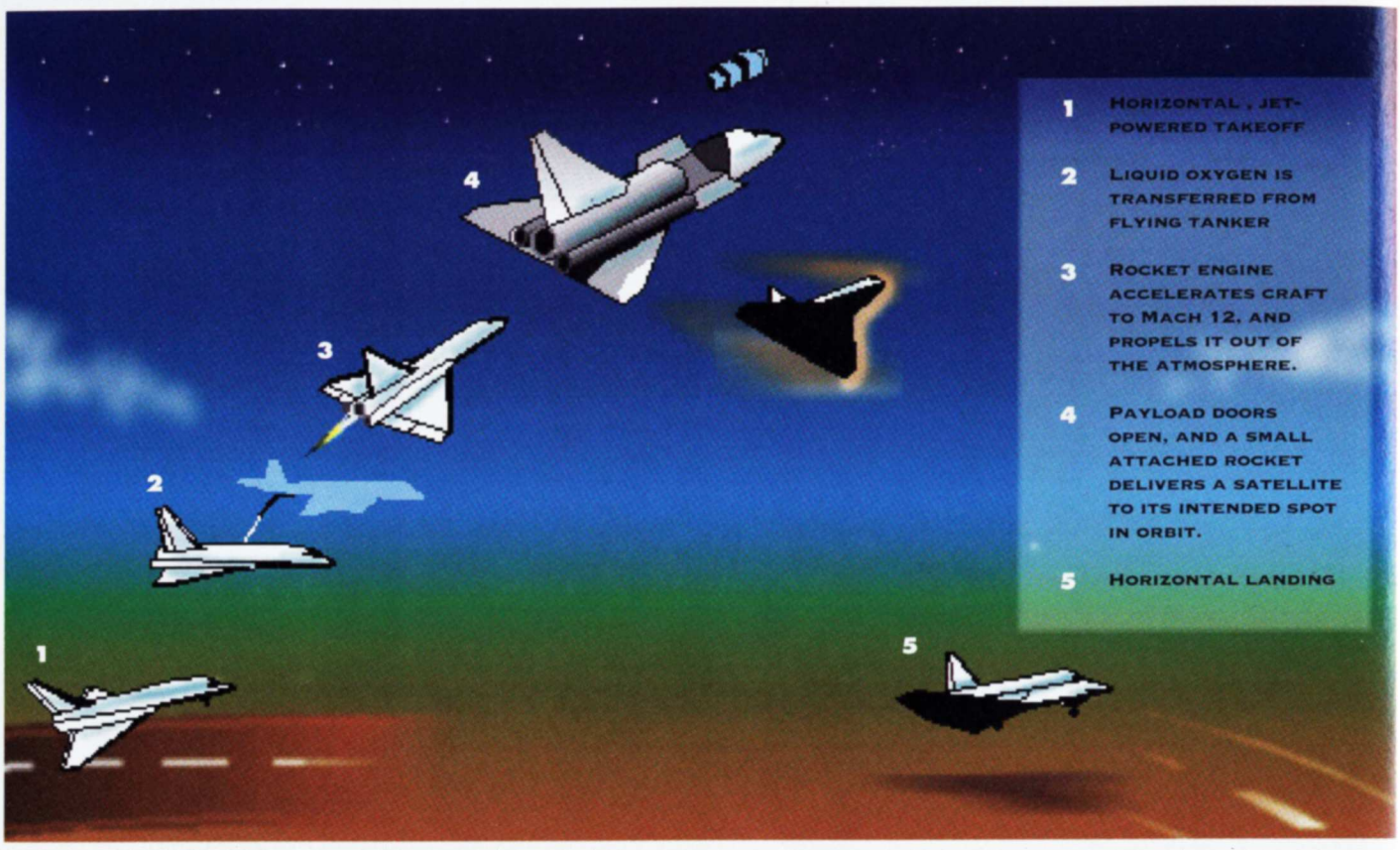
Aviation's Next Great Leap

The technology is at hand
to build rocket-powered aircraft that
could travel at hypersonic speeds,
whisking you from New York
to Paris in an hour.



DESPITE ITS AURA as a cutting-edge industry, aerospace has stagnated for decades. The same types of jet airplanes that went into service in the 1960s still prevail in commercial and military flight. In the United States, there hasn't been a significant new rocket-engine program since the space shuttle main engine was developed 20 years ago. Nothing about the Boeing 777 would perplex Eisenhower-era aircraft designers.

Today, however, the availability of reliable, reusable rocket engines could make possible the next major step in aerospace transportation: the rocketplane. Rocketplanes combine rocket propulsion with aviation, allowing aircraft that take off and land from conventional airports to fly up and out of the atmosphere. Rocketplanes will lower the cost of satellite launch, accelerate the delivery of packages, and, ultimately, provide a way for people to zip from one side of the world to the other in an hour or so. Farfetched though this



A rocketplane would take off from a runway under the power of a conventional jet engine, firing its rockets only after climbing to the fringes of the atmosphere. In Pioneer's scheme (top), the aircraft would pause on its way up to suck liquid oxygen (needed for rocket operation) from a flying tanker plane.

A competing approach, advanced by Kelly Space and Technology, requires a conventional aircraft to tow a rocketplane up to high altitude (right). In both methods, the rocketplane would land unaided, like an ordinary airplane.

vision may seem, the technology is at hand.

The idea of a rocket plane is not new. The first such aircraft—the German Heinkel He-176—flew in 1939. It was in the rocket-powered X-1 that Chuck Yeager first broke the sound barrier, 50 years ago last October. During the 1980s and early 1990s, NASA and the U.S. Department of Defense cooperated on the National Aerospace Plane Project—an effort, since cancelled, to develop technologies that would make possible a vehicle that would take off like an ordinary aircraft, accelerate into orbit around earth, then return through the atmosphere for a runway landing.

But recent advances in technology—from more efficient rockets to more reliable and robust thermal shields—have pushed the rocketplane closer to practical reality. At the same time, the market for the services such a vehicle could offer is growing. The need to launch satellites economically may provide the first stimulus for developing a rocketplane. In the future, though, the main day-to-day use of these hypersonic vehicles may well lie in delivering passengers and valuable packages around the world.

It's no mystery why aircraft designers have taken so long to embrace rocket engine technology. First, rockets are inefficient, consuming fuel seven times as fast as turbojet at full power. And while a jet engine "breathes" air from the atmosphere to burn its fuel, rockets are designed to work in the vacuum of space and so must carry not only fuel but also oxidant—usually in the form of liquid oxygen. This requirement imposes a greater weight burden on a rocket than a jet.

Second, rockets have generally not proved to be as reliable as gas-turbine engines. This unreliability stems in part from the fact that these engines operate at extremely high temperatures. In addition, aircraft designers and engineers have relatively little experience with rockets, compared with their billions of hours of experience with jet engines.

But rockets have some countervailing advantage. Although they guzzle fuel, they weigh only a fraction of what gas turbines do. The best jet engines now in development generate about 9 times as much thrust as the

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DIAGRAM BY PERUGI DESIGN

weight of the engine. By contrast, even a very heavy rocket engine produces a thrust-to-weight ratio of 50. Moreover, with present technology only a rocket can attain the Mach 25 speed needed to overcome the tug of gravity and enter earth's orbit. (Mach 1 is the speed of sound in air—roughly 740 mph, or 1,200 kilometers per hour.) Even the fastest air-breathing jet engine slogs along at only about Mach 4.

Getting Up To the Wild Black Yonder

Commercially successful rocketplanes will depend on developments in two key technologies: a reliable, reusable rocket engine and a robust thermal protection system to prevent damage during re-entry. In both cases, advanced solutions are at hand.

U.S. researchers have focused on improving component technologies and advanced materials, not on manufacturing actual rocket-engine products. In the former Soviet Union, however, researchers have continued to advance the development of rocket engine families. In particular, the Soviet space shuttle program led to a new generation of advanced reusable rocket engines fueled with kerosene (that is, conventional jet fuel), hydrogen, or a combination of the two. For example, the reusable RD-120, a kerosene-burning engine developed as an upper-stage engine for the Zenit booster, has been certified by its U.S. importer Pratt and Whitney as good for 10 flights—plus another 10 after a major overhaul.

Aerospace engineers also recognize that the thermal protection system on the space shuttle is not suitable for a truly robust vehicle. Although the shuttle is reusable, its heat shield is easily damaged. Moreover, ordinary weather conditions such as rain and wind-driven dust damage the heat shield. Following each landing, the shuttle must undergo a costly and time-consuming refurbishing involving toxic chemicals and special procedures, to replace the lost and damaged tiles so that the spacecraft can safely ascend to orbit again.

NASA's efforts to correct these problems have yielded impressive results. Designers have a much broader selection of tiles, blankets, metal surfaces, and advanced composites and ceramics, all of which can make new-generation rocketplanes capable of withstanding wind and weather that would strip the heat shield off the shuttle in minutes. One of the new materials—the AETB-TUFI-C thermal protection tile developed by NASA's Ames Research Center—has survived, undamaged, a test flight on an F-15. This result was all the more remarkable because the fighter flew through a rainstorm that scoured the paint off its surface.



Such advances have fortified the prospects of building a reusable rocketplane. But other design questions remain before such a craft becomes practical. First, to take advantage of the trillions of dollars of existing airport infrastructure, a rocketplane needs to be able to take off and land in a conventional, horizontal manner.

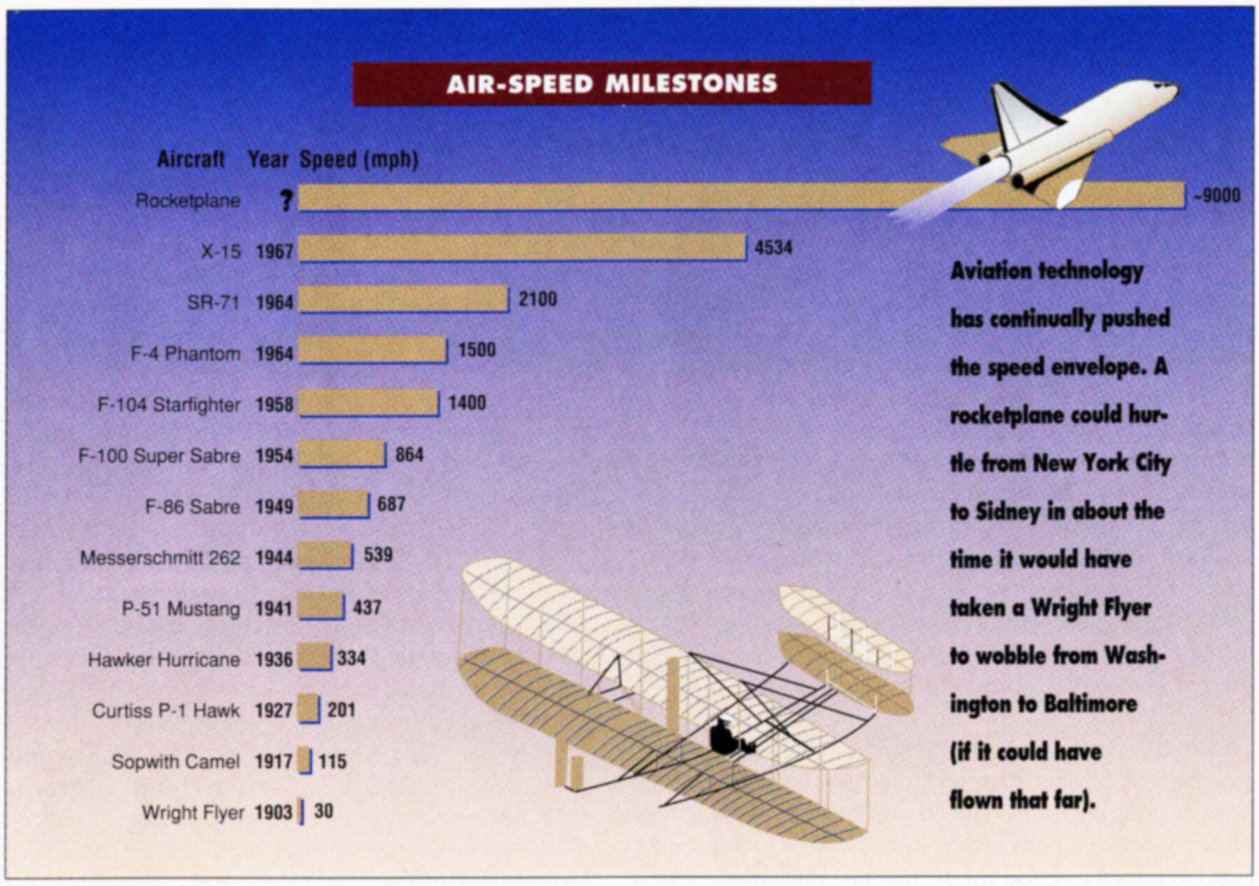
Moreover, a rocket engine works best in the vacuum of space; the denser the air, the more fuel the rocket must burn to develop the same amount of thrust. The atmosphere's thick soup of air also imposes a drag penalty, forcing the rocket to squander huge amounts of fuel. Thus a rocket-powered aircraft needs some other means of propulsion to lift it from the ground to the upper reaches of the atmosphere; once reaching the fringes of the atmosphere, the rocket could ignite and propel the craft into space.

Aeronautical engineers have developed three principal schemes to accomplish this. In one, the rocketplane is attached to the belly of a jet aircraft, which takes off and flies to a high altitude. Then the rocketplane drops off to complete its flight. Chuck Yeager used this technique in 1947 to achieve the first human travel at supersonic speed.

In a modern variation of this approach, a jet aircraft tows a rocketplane to high altitude with a tether, much the way conventional airplanes launch gliders. This scheme is being developed at Kelly Space and Technology in San Bernardino, Calif. Kelly's Eclipse aircraft is towed by a Boeing 747 to an altitude of about 14 kilometers. There, the Eclipse fires its rocket engine, disconnects from the tow line, and climbs to about 150 kilometers. The Eclipse then glides to an unpowered landing.

An advantage of these two techniques is that the rocketplane itself needs only one engine—the rocket. On the other hand, any vehicle that depends on another aircraft to launch it has a serious drawback. If the rocketplane lands in the wrong place, for example, it will have to await the arrival of a carrying or towing plane before it can get airborne again. Moreover, takeoff in such a tandem configuration would require longer and wider runways than those at existing airports. Moreover, if the rocket engine does not light after disconnecting from the carrier aircraft, the rocketplane would probably be lost.

Our company—Pioneer Rocketplane—favors a different launch-assist scheme. In the Pioneer approach, the Pathfinder aircraft would take off in a conventional manner and climb to nine kilometers under the power of conventional turbofan jet engines. There it would rendezvous with a large subsonic aircraft, such as a KC-135 transport or a Boeing 747, that would serve as a flying tanker. To prepare for the second phase of flight, the rocketplane would dock with this tanker and suck about 290,000 kilograms of liquid oxygen from it. Such transfers are common practice in military aviation, although the propellant being moved is jet fuel rather than liquid oxygen.



After disconnecting from the tanker, the aircraft would light its rocket engine and climb to 150 kilometers, reaching a speed of Mach 12. The rocketplane would then travel above the outermost fringes of the atmosphere, during which time a satellite attached to a small rocket upper stage could be released for transfer to orbit. The aircraft would then descend back into the atmosphere. After slowing to a subsonic speed, the turbofan engines would restart, propelling the aircraft to a landing field. Because it could take off from any medium-sized airfield, the Pioneer rocketplane would provide great flexibility in choice of launch site and abort options.

Riding a Rocketplane For Fun and Profit

The first thing that comes to many people's mind in thinking about rocket planes is the potential for rapid personal travel. While that possibility exists, other applications promise a steadier revenue stream and will probably develop first.

SATELLITE LAUNCH: Despite a healthy business from launching government and commercial satellites, the international space launch industry has for the past two to three decades suffered a period of almost complete technological stagnation. Most of the launch systems now in use—including the Delta, Atlas, Titan, Soyuz, Molniya, and Proton—were already flying in more or less their current forms in the mid-1960s. While a few additional systems, such as the European Ariane, have been introduced in the intervening decades, technological improvements have been so minor that older systems are still competitive. As a result, freight rates from the earth's surface to orbit remain at about $10,000 to $20,000 per kilogram—the same as in the 1960s. This persistently high cost severely inhibits the commercial development of space.

One major reason for this high cost is the reliance on expendable boosters—a rocket is launched to orbit, where it releases the satellite or other payload, and then the rocket crashes back into the ocean, never to be used again. Not surprisingly, this practice has contributed enormously to inflating launch costs. Consider what the cost of air freight or air travel would be if each airliner were disposed of after a single flight. That analogy, if anything, is understated; an Atlas launch vehicle, good for one use, costs three times as much as a Boeing 737.

Recently, private consortia have appeared, aiming to establish large fleets of low-orbiting communications satellites (*See "Let's Do Launch," p. 33.*) The U.S. launch industry has been unresponsive to the needs of these customers, who cannot afford today's high launch costs. These new satellite consortia represent an extraordinary opportunity for creating a new U.S.-based launch system. Moreover, in meeting the needs of economy-minded commercial customers, a new inexpensive U.S. launch system could capture a great deal of government business as well.

The economics of proposed rocket planes look promising. Both the tow-launched Kelly Eclipse and the tanker-assisted Pioneer Pathfinder rocketplanes could climb to an altitude of about 150 kilometers and then release a satellite, which

DIAGRAM BY PERUGI DESIGN

would be strapped to a small rocket that would carry the satellite to the desired orbit. These rockets—the only expendable items in the system—would cost about $2 million each. With such a low cost of expendable hardware, the price of the rocketplane launch services could probably be in the $4–8 million range and still allow for substantial profit, even considering maintenance expenditures and the fixed cost of the initial investment. This compares well with the $23 million it now costs to launch such a satellite from earth aboard an Orbital Sciences Corp. Taurus and to the $15 million per satellite price for launching a group of six satellites on a Lockheed Martin Atlas 2A.

In fact, rocketplanes are the only technology on the horizon that will be able to support the launch requirements of a fleet of 1,000-kilogram satellites affordably. Due to expected component failures, a typical satellite will probably require replacement about once every six years. Thus, keeping 1,500 satellites in operation will require replacing about 250 satellites per year. These replacement launches will have to be done rapidly, flexibly, and one at a time to fix "holes" in the constellations as they appear.

FAST PACKAGE DELIVERY: In today's worldwide market, long distances demand faster transportation. Rocketplanes could carry substantial payloads from one side of the world to the other in a few hours.

In 1994, a group of leading aerospace contractors released the Commercial Space Transport Study, which documented this need. These contractors interviewed Federal Express and many other courier services, who expressed confidence that a strong market would arise for the kind of rapid global package delivery that a suborbital rocketplane could offer. A strong market would exist for such a service, these companies said, even if the price of delivery were as high as $2,000 per kilogram.

A primitive rocketplane service, however, could probably be cheaper than that. The cost of a flight would be about $500,000, to which we will assume an addition of 100 percent margin for overhead and profit, for a per-flight price of $1 million. For a payload of 2,500 kilograms, that comes out to $400 per kilogram. That's pretty steep for ordinary document delivery, but attractive for those who absolutely, positively, have to ship something a long distance in a matter of hours. At these prices, rocketplane package delivery would carry items such as electronic devices, biological reagents, human organs, precious stones, microcircuits, just-in-time parts needed at a factory, and extremely time-sensitive business documents. According to the aerospace companies' study, by the year 2000 the annual market for such ultra-fast delivery services could reach about 1 million kilograms, yielding revenues of $400 million. Based on industry trends, this market could be expected to grow at 7 percent yearly.

Some people may scoff at the notion of rocketplane package delivery. But think of space travel as analogous to seafaring. For thousands of years, people have tried to extract wealth from the sea, primarily by fishing. This activity compares with satellite use, which attempts to extract wealth from space by provision from there of communication or remote-sensing satellites. But the oceans have generated far more wealth through maritime commerce, which has taken advantage of the fact that the sea allows relatively easy transport of goods over long distances, and adjoins most of the large cities of the world. Similarly, space is a global ocean that adjoins every place on earth and allows potentially extremely rapid transport. Most attempts to derive wealth from space have focused on putting satellites there. But in the long run the fast-package-delivery capability of rocketplanes traveling through space will probably dwarf the "fishing" commerce carried on by satellites operating in space.

DEFENSE: The U.S. military has recently issued reports, such as the Air Force's "Spacecast 2020" study, calling for the development of an ultra-high-speed vehicle capable of operating both in the atmosphere and in space. The Pentagon is seeking a craft capable of observing, intercepting, and striking an enemy's aircraft. Rocketplanes, with their capability for fast response, high speed, and long range, compare favorably with other alternatives for these purposes.

Rocketplanes could intercept an adversary's air transport deep within that country's airspace, for example, performing the same commerce interdiction role in the air that navies have historically performed at sea. Used as a strike vehicle, a rocketplane could ascend on a suborbital trajec-



LET'S DO LAUNCH

The new commercial communications satellite consortia represent an extraordinary opportunity for creating a new U.S.-based launch system. The U.S. launch industry, with its high prices, has been unresponsive to the needs of these consortia, which include Loral Globalstar, Teledesic, and Iridium.

The consortia have therefore shown a willingness to deal with startup companies sponsoring new ideas such as rocketplanes, which have the potential to reduce costs sharply. Last fall, for example, Motorola awarded Kelly Space and Technology an $89 million contract to launch 20 of its Iridium satellites. Moreover, in meeting the needs of economy-minded commercial customers, a new inexpensive U.S. launch system could capture a great deal of government business as well.

tory, release its bombs or missiles, and then bounce off the atmosphere well above fighter altitude to hit a series of targets in an unpredictable fashion.

As a strategic weapon, the rocketplane combines the speed and range of intercontinental ballistic missiles with the flexibility and recallability of a piloted bomber aircraft. If the United States were ever again to face a nuclear balance of terror, rocketplanes would keep national leaders from needing to "launch on warning." If early data were received indicating that an enemy strike were under way, warhead-bearing rocketplanes could scramble to safety in the air. Only after hostile action was confirmed would the rocketplanes be launched toward their targets.

Rocketplane passengers will experience several minutes of weightlessness, perhaps enjoying a brief float around the cabin as the aircraft enters the free fall of earth orbit.

Last fall, President Clinton attempted to eliminate military spending on rocketplane development using his line-item veto. The program has major support and a strong rationale, however; sooner or later, it will be funded.

GLOBAL PASSENGER SERVICE: If rocketplanes succeeded at global package delivery, passenger versions could also evolve. These could fly from New York to Paris in less than one hour or New York to Sydney in less than two hours. One frequently raised objection to rocketplane passenger service is financial. A long-distance subsonic aircraft typically requires a fuel load about equal to the weight of the airplane plus its payload; in contrast, a long-distance rocketplane might need propellant equal to four times the craft's mass. But the comparison is not that straightforward. Most of the rocketplane's propellant load is liquid oxygen, which costs 10 cents per kilogram—one-fourth as much as the jet fuel that an ordinary aircraft consumes. Taking this difference into account reveals that the propellant cost for a long-distance rocketplane ride is likely to be less than double that of a subsonic airliner. Because the rocketplane could be used several times in the period it takes a long-distance subsonic airliner to fly a single trip, the rocketplane's per-flight costs would not be far out of line. As long as maintenance costs can be kept to levels comparable with that of existing aircraft, a rocketplane could be commercially competitive.

Economic viability of passenger service presumes that riders of a rocketplane would be willing to pay a premium fare for the convenience of such swift travel, just as riders of the supersonic Concorde do today. And a rocketplane would provide more than a quicker journey. For several minutes in the middle of each flight, the vehicle will enter the free fall of earth orbit. During this time, passengers will experience weightlessness, perhaps enjoying a brief float around the cabin. Looking out the windows they will see a black, starry sky—the universe in its full glory as viewed from space. Zero-gravity may lead to instances of space sickness, of course; indeed, some might say that the novelty of such a mode of transportation will deter, rather than attract, passengers. Then again, that is exactly what the railroad owners said about airplanes in the early part of this century.

One might argue that the explosion of global electronic communications will supplant the need for rapid personal travel. The evidence of the past century, however, indicates exactly the opposite. Starting with the telegraph, and continuing with the telephone, radio, TV, fax, and Internet, the growth of electronic communications has contributed to a vast expansion of global commerce and rising demand for intercontinental personal travel. Moreover, as the means of electronic communication become faster, the more anachronistic today's subsonic flight travel times will seem. A faster-moving society will require faster airplanes.

Creating A New Space Industry

Since rocketplanes are a near-term technology with widespread commercial application, it should be possible to finance their development primarily with private investment. Nevertheless, development of novel flight systems always involves significant business risk, which could be mitigated by government participation.

Reference to our current era as the Space Age is a misnomer—like calling the 1910s the Air Age. Except for the military, the world did not really feel the impact of air travel until the technology became routine and commonplace and affordable to more than an elite few. Likewise, if a *real* Space Age is going to arrive, there needs to be a market for rocket vehicle technology that supports the manufacture of spacecraft components not in lots of ones or twos, but in hundreds or thousands.

Producers of these planes will have to start using the production methods common in commercial aviation rather than the costly small-lot production techniques that dominate the space industry today. Moreover, we will need a worldwide launch infrastructure that supports not hundreds of flights per year, but hundreds of flights per day. The only markets large enough to stimulate investment in such production capacity and launch infrastructure are long-distance package delivery and passenger transport.

For the same reason that military and then postal aircraft preceded passenger aircraft, satellite launch, military, and fast package-delivery rocketplanes will no doubt precede passenger rocketplanes. Nevertheless, the day will surely come when thousands of rocketplanes cross the globe daily, serving business and vacation travelers from New York to Tokyo—perhaps even into orbit. ■

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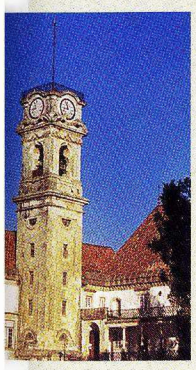
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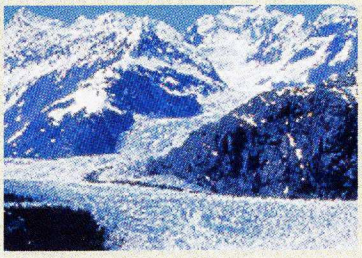
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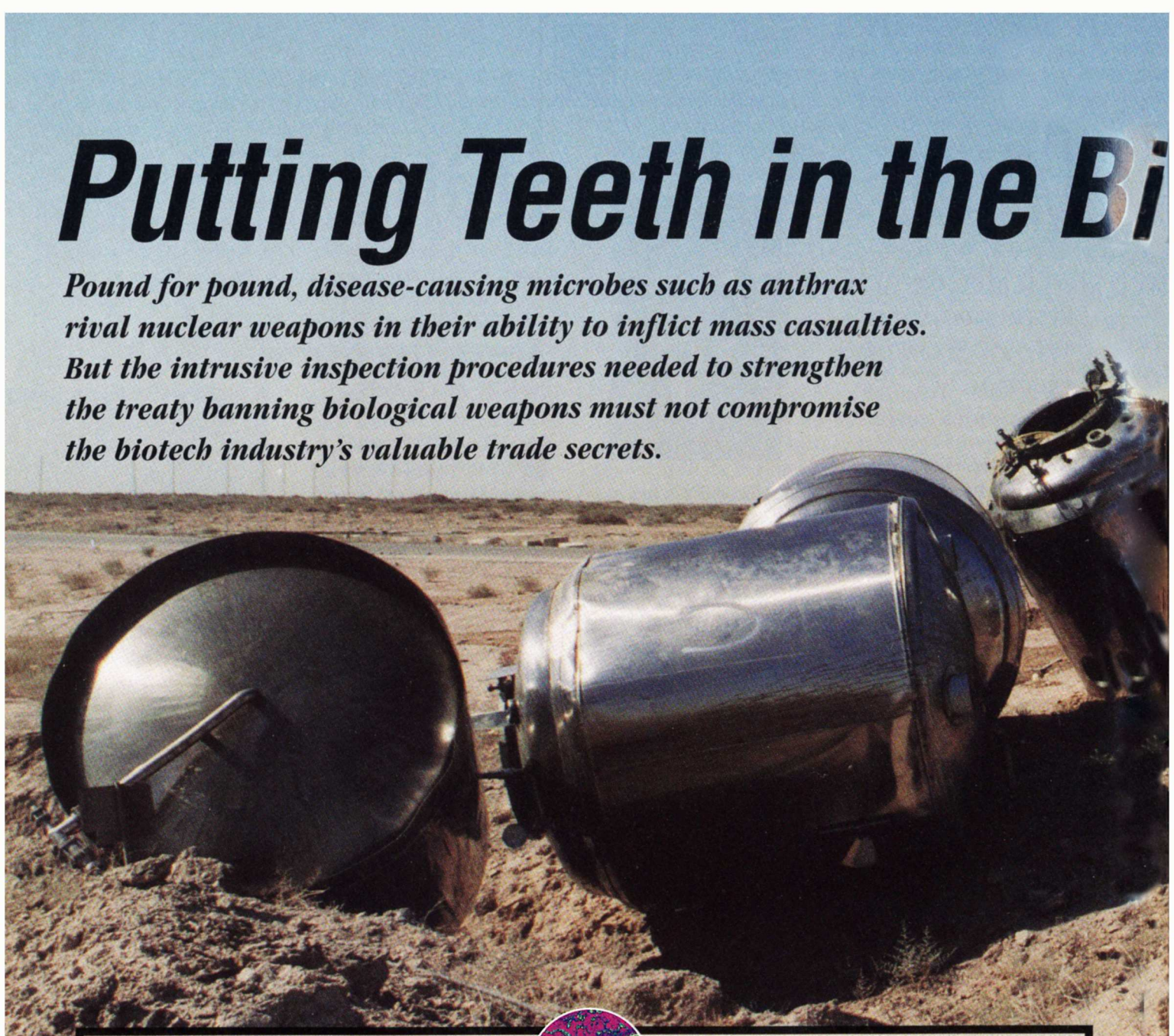
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Putting Teeth in the Bi

Pound for pound, disease-causing microbes such as anthrax rival nuclear weapons in their ability to inflict mass casualties. But the intrusive inspection procedures needed to strengthen the treaty banning biological weapons must not compromise the biotech industry's valuable trade secrets.





IT took 20 years, but in April a treaty finally went into effect banning chemical weapons. While the Chemical Weapons Convention is an important step toward a safer world, it may have the undesired effect of encouraging some countries to redouble their efforts to acquire *biological* weapons—disease-causing microbes and natural poisons such as anthrax, pneumonic plague, and botulinum toxin. Biological weapons are not only more potent than chemical weapons but they are easier to produce in small, clandestine facilities.

A biological attack could create an almost unimaginable catastrophe. According to an estimate by the U.S. Congress's former Office of Technology Assessment, 100 kilograms of anthrax, released from a low-flying aircraft over a large city on a clear, calm night, could kill 1–3 million people. This figure is comparable to the casualties from a one-megaton hydrogen bomb. When disseminated as an aerosol, anthrax spores (analogous to microscopic seeds) are inhaled deep into the victim's lungs and travel to the lymph nodes, where they germinate and multiply. The bacteria then secrete potent toxins, giving rise in about three days to a devastating illness. For the victims to have any chance at all of surviving, antibiotics must be administered intravenously before the onset of acute symptoms.

Because biological weapons are so potent yet much cheaper and easier to produce than nuclear weapons, they have been called "the poor man's atomic bomb." In addition to their potential use as strategic weapons of

ological Weapons Ban

By Jonathan B. Tucker



Fermentation vessels that Iraq allegedly used to produce germ-warfare agents such as anthrax lie strewn across the desert after destruction of the Al Hakam facility by UN inspectors.

mass destruction, biological agents are well-suited for covert operations such as sabotage, terrorism, counter-insurgency warfare, and assassinations.

The threat of biological warfare is not just an academic concern. In October, the United Nations Special Commission (UNSCOM) monitoring the elimination of Iraq's weapons of mass destruction concluded that Iraq was still trying to conceal the full scale and scope of its biological weapons program. Iraq acknowledged in 1995 that prior to the Gulf War, it had produced large quantities of anthrax spores, botulinum toxin, and a fungal poison called aflatoxin, filled them into at least 166 aerial bombs and Scud missile warheads, and stockpiled them ready for use. Although Iraq claimed to have destroyed its biological arsenal after the war, U.N. inspectors suspect that Iraq may still be hiding a cache of anthrax spores and germ filled warheads.

In November, Iraq barred U.S. experts from participating in UNSCOM weapons inspection teams, apparently because the Americans were hot on the trail of banned weapons activities. While the on-site inspections were on hold, the Iraqis moved equipment and tampered with surveillance cameras at ostensibly civilian facilities, such as vaccine plants, that could potentially be used for producing biological warfare agents as well. In a letter to the U.N. Security Council, UNSCOM Executive Chairman Richard Butler warned that without effective monitoring, the Iraqis could easily adapt laboratory or industrial equipment in "a matter of hours" to produce stocks of biological warfare agents.

Iraq is only the best-known example of several countries—among them China, Egypt, Iran, Iraq, Libya, North Korea, Sudan, Syria, and Taiwan—known or suspected to be pursuing a biological warfare capability. The U.S. government also believes that rogue elements within the Russian military may be continuing Soviet programs to develop biological weapons, despite President Boris Yeltsin's 1992 order that such activities cease.

Particularly alarming is the possibility that domestic or international terrorist groups could acquire biological weapons and use them against civilian targets. The Japanese cult Aum Shinrikyo, which in 1995 carried out a deadly attack with a chemical nerve agent on the Tokyo subway, was found to have an advanced microbiological facility to produce anthrax and botulinum toxin. In 1994, cult members repeatedly released anthrax spores from the roof of a high-rise building in Tokyo in an attempt to inflict mass casualties. Fortunately, technical problems with the delivery system rendered these attacks ineffective.

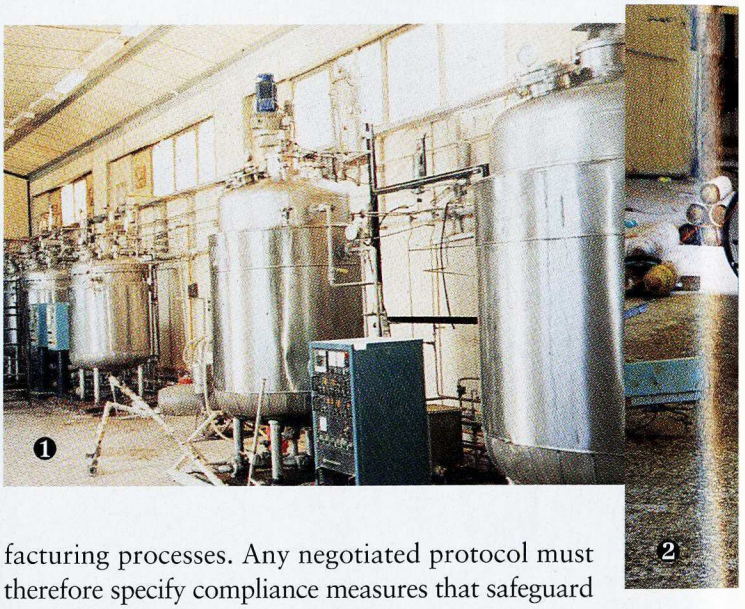
In principle, production of biological weapons is already banned by the Biological Weapons Convention (BWC), a treaty that has been in force since 1975. But the BWC was born with a crippling defect: it lacks a formal mechanism for investigating alleged violations, and thus has come to be regarded as little more than a gentleman's agreement. At the time the treaty was negotiated in the early 1970s, verification procedures were considered unnecessary because biological weapons were believed to have little military value. Shortly after the BWC took effect, however, the advent of recombinant-DNA technology raised the specter of engineering new pathogens that might be more controllable, lethal, or persistent, leading some defense analysts to reassess their utility as warfare agents.

The coming year will provide an opportunity for progress toward crafting an inspection regime to strengthen the BWC. A group of member-countries, known as the Ad Hoc Group, will meet in Geneva for a few weeks in January and then for three more negotiating sessions later in the year. Their goal: to develop monitoring mechanisms to check that member-countries are obeying the treaty's prohibitions. This legally binding "compliance protocol" will specify how international inspectors from a future BWC monitoring organization will be allowed to enter and examine facilities suspected—or merely capable—of producing biological warfare agents.

Possible elements of a compliance protocol include:

- requiring countries to declare the existence of all relevant biological facilities.
- routine on-site visits to check the accuracy of such declarations.
- occasional "challenge" inspections to pursue suspected treaty violations at declared or undeclared facilities.
- field investigations to pursue allegations of biological-weapons use and suspicious outbreaks of disease.

Whatever monitoring measures are agreed to will be equally binding in all participating states. Operating under a kind of "golden rule" for treaty negotiations, members of the Ad Hoc Group must be prepared to accept the same types of intrusive monitoring they wish to apply to others. Each nation must therefore find the right balance between a regime that is intrusive enough to ensure that other countries are following the rules and one that allows them to safeguard sensitive industrial and national-security information. U.S. pharmaceutical and biotechnology companies, for instance, have expressed concern that intrusive inspections could open the door to industrial espionage. Companies routinely invest millions of dollars to develop and test new medications, production microorganisms, and manufacturing processes. Any negotiated protocol must therefore specify compliance measures that safeguard proprietary information.



While most of the countries in the Ad Hoc Group agree that the compliance protocol should provide for short-notice inspections of suspect facilities, they have been unable to reach consensus on a mechanism for triggering them. Last summer, however, the group took an important step forward by deciding to prepare a draft treaty—a "rolling text," in diplomatic parlance—in which non-agreed language is set off in brackets. Right now, the draft is still full of brackets.

Contending with Ambiguity

The negotiators have their work cut out for them. The equipment and facilities used to cultivate biological-war-

JONATHAN B. TUCKER directs the chemical and biological nonproliferation project of the Center for Nonproliferation Studies at the Monterey Institute of International Studies in Monterey, Calif. In 1995 he served as an inspector on a UN Special Commission team investigating biological weapons activity in Iraq, including the suspected Al Hakam facility near Baghdad.

FRONTIS AND PHOTOS: UNITED NATIONS SPECIAL COMMISSION

fare agents are essentially the same as those used for the commercial production of vaccines, antibiotics, vitamins, biopesticides, feed supplements—even beer and yogurt. The spread of these "dual-capable" technologies for industrial microbiology has given rise to a burgeoning global potential for biological warfare, since countries can easily cloak their acquisition of illicit agents under the guise of legitimate research and production. Moreover, it takes only an extremely small quantity of a microbial pathogen—on the order of a few kilograms—to produce a militarily effective weapon. A deadly arsenal could therefore be made over a period of weeks, eliminating the need for long-term stockpiling.

Cultivation of disease-causing microbes cannot be banned outright because the same organisms that can kill thousands of people also have legitimate medical and industrial uses. Pharmaceutical companies, in particular, routinely grow large quantities of dangerous pathogens for the production of vaccines. Similarly, potent toxins such as ricin and botulinum play an increasingly important role in the treatment of cancer and neurological diseases.

Recognizing these peaceful applications, the BWC specifically prohibits the development and production of biological and toxin agents only "in types and quantities that have no justification for prophylactic, protective, or other peaceful purposes." As a practical matter, however, it is difficult to distinguish between offensive activities and benign ones. Merely looking at a fermentation tank reveals little about its contents. Only the analysis of an actual sample can tell which microbes are present, and that will require on-site inspections of dual-capable facilities such as vaccine plants. Inspectors of a suspicious facility might take samples from various steps in the production process, ranging from seed cultures to finished products. Samples might also be swabbed from the surface of production equipment, benches, walls, or floors, or collected from soil, water, air, plants, and animals outside the buildings. These samples would then be analyzed, using some combination of techniques now common in the biotechnology industry and medical diagnostics.

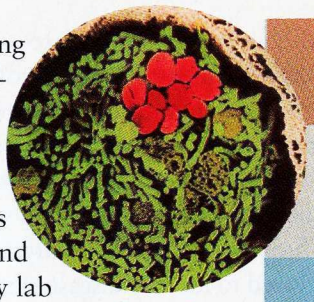
Three sophisticated analytical methods are routinely employed to identify disease-causing bacteria and viruses. In classical bioassay, scientists cultivate a sample to grow live microorganisms; these microbes can then be identified using a variety of chemical or physiological tests. Immunoassay techniques employ specific antibodies to detect unique molecular markers on the surface of target microorganisms, as well as protein toxins. Genetic analysis involves the use of "gene probes"—short strands of synthetic DNA that bind to complementary DNA sequences unique to each microbial species.

Gene probes are often employed in conjunction with a powerful technique called the polymerase chain reaction (PCR), which multiplies a given DNA sequence more than a million-fold. With the aid of PCR, scientists can identify a species of bacteria even if only a few dozen cells are present in the sample—avoiding the need to culture them into large colonies over a period of days or weeks.



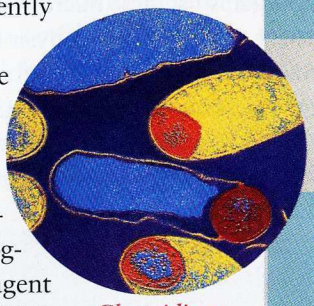
Eradicating biological weapons production requires highly intrusive measures, as demonstrated by the UN Special Commission's intervention at Iraq's Al Hakam factory:
❶ Fermentation tanks that Iraq claimed were producing legitimate products were later determined to have cultivated anthrax and botulinum toxin.
❷ Inspectors examine a partially destroyed fermentation tank.
❸ Equipment used to cultivate pathogens is destroyed.
❹ Finally, the buildings are blown up.

In some cases, sampling and analysis can yield compelling evidence of illicit activities. When Japanese police raided the Aum Shinrikyo cult's headquarters near Mount Fuji, they found an advanced microbiology lab producing anthrax bacteria and botulinum toxin, apparently intended for terror attacks.

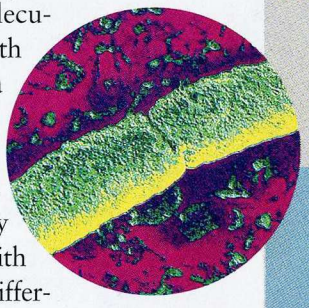


Bacillus anthracis

Generally, however, the results of sampling and analysis are less clear. Analytical techniques occasionally produce "false positives" by appearing to recognize a biological-warfare agent that isn't actually present. This problem may arise when the target DNA sequence or molecular marker is present in both a pathogenic agent and a harmless microorganism. To avoid false positives, inspectors should confirm a positive result obtained by one analytical technique with another method based on different scientific principles.



Clostridium botulinum



Yersinia pestis

Disease	Biological-warfare Agent	Incubation period
Anthrax (pulmonary)	*Bacillus anthracis* (bacterial spore)	1-5 days
Botulism	Botulinum toxin, produced by *Clostridium botulinum* (bacterium)	2–36 hours
Encephalitis, Venezualan equine	VEE virus	2–5 days
Plague, pneumonic	*Yersinia pestis* (bacterium)	2–5 days
Ricin intoxication	Toxin extracted from the seeds of the castor bean plant, *Ricinus communis*	1–10 hours
Smallpox	Variola virus (eradicated except for laboratory specimens in U.S. and Russia)	12 days

Samples may also be contaminated with pathogenic microbes naturally present in the environment. Anthrax spores, for example, are often found in sheep and cattle grazing areas in concentrations of 100 to 500 spores per 100 grams of soil. These levels, though well below the 10,000 or so spores that must be inhaled to cause infection, are easily detectable with PCR. The pharmaceutical industry therefore worries that anthrax spores naturally present in the environment might be tracked into a vaccine plant on the bottom of workers' shoes and detected by international inspectors—raising suspicion of a BWC violation where none is warranted and damaging a firm's hard-won reputation. "The release of erroneous information implying serious wrongdoing could cause irreparable harm to a company's relationship with its shareholders and the general public," observes William Muth, a scientist at Lilly Research Laboratories in Indianapolis.

Thus in the absence of a "smoking gun," such as a rack of bombs or warheads filled with biological agents, sampling and analysis would not provide unequivocal proof of a treaty violation. Detecting anthrax would not necessarily be incriminating, for example, if the facility in question were culturing the agent for a legitimate purpose, such as the production of a protective vaccine, or if anthrax were endemic to the surrounding region. Moreover, highly sensitive detection technologies such as PCR could find minute traces of anthrax DNA, while revealing little about the total amount of agent produced at the site.

On the other side of the coin, since it is not possible to sample everywhere, inspectors may fail to detect actual violations of the BWC. Thus the inability to find an illicit biological-warfare agent at a suspected facility does not necessarily mean that the plant is treaty-compliant. A covert proliferator might exploit a series of negative findings to claim a clean bill of health. Because of the possibilility of false positives or false negatives, evidence of BWC violations obtained by sampling and analysis must be interpreted in the light of other types of information.

Protecting Trade Secrets

The pharmaceutical industry worries that sampling and analysis used during on-site inspections could jeopardize industrial trade secrets. The chemical industry initially had similar reservations about the intrusive inspections allowed by

PHOTOS: PHOTO RESEARCHERS, INC/A.B. DOWSETT, ALFRED PASIEKA

Main symptoms	Fatality rate (untreated)	Contagiousness	Previous use as weapon
High fever, labored breathing, rapid pulse, shock	90%	none	Possible covert use during the Rhodesian civil war (1978-80)
Fatigue, nausea, headache, cramps, giddiness, respiratory paralysis	65%	none	Before the 1991 Gulf War, Iraq filled botulinum toxin into bombs and warheads
Infection of central nervous system	<1%	none	None known
Infection of lungs, fever, headache, pneumonia, hemorrhages, heart failure	nearly 100%	high	During World War II, Japan dropped bombs containing plague-infested fleas on Chinese towns
Ingestion causes nausea, vomiting, bloody diarrhea, stupor, convulsions, shock, and liver and kidney damage	Lethal dose is about 1 microgram per kilogram of body weight	none	In 1978, the Bulgarian Secret Service used ricin to assassinate a dissident living in London
Headache, chills, fever, lesions of skin and mucous membranes	25-40% (if unvaccinated)	very high	In 1763, British forces at Fort Pitt (Pa.) gave contaminated blankets to rebellious Indians

the Chemical Weapons Convention. For example, inspection of a chemical plant might reveal a proprietary manufacturing process that provides a small but significant competitive edge, such as lowering production costs of a commodity chemical by a few cents per ton. In the pharmaceutical and biotech fields, however, the financial stakes are much higher. Because drug development is so research-intensive, it costs a large pharmaceutical house between $350 million and $500 million to bring a new product to market. According to the Pharmaceutical Research and Manufacturers of America, an industry trade association based in Washington, U.S. pharmaceutical manufacturers spend 19.4 percent of sales on R&D, compared to an average across all industries of 3.8 percent. U.S. drug companies also lead the world in innovation, accounting for 36 percent of global pharmaceutical research and development.

Biotechnology-based medicines represent a major growth sector for the U.S. pharmaceutical industry. In 1995, U.S. firms and organizations were responsible for about 80 percent of patents for genetically engineered health-care and pharmaceutical products issued by the U.S. Patent Office. From 1989 to 1996, the number of biopharmaceuticals being developed by U.S. companies to treat diseases ranging from the common cold to cancer soared from 80 to 284. Over the same period, the number of U.S. companies developing new-generation biotechnology drugs more than doubled, from 45 to 113.

Biotech companies fear that foreign inspectors visiting their plants could gain insight into their production techniques or even obtain a covert sample of a genetically engineered microorganism, whose proprietary DNA sequences could then be determined. Such information can be worth vast sums. For example, the genetically engineered bacterium that produces human insulin is valued at more than $1 billion, according to Lilly's Muth. With such huge investments at stake, the U.S. pharmaceutical industry is determined to protect its confidential proprietary information.

Most pharmaceutical industry representatives endorse the concept of "managed access," an approach developed for on-site inspections under the Chemical Weapons Convention. In this procedure, the inspection team and the host country negotiate the amount of access to be provided to sensitive areas of the inspected site. For example, facility managers might turn off computers, lock up documents, place

How Countries Might Cheat



Determined violators of the BWC may seek to evade any monitoring regime that is put in place. A violator might, for example, attempt to modify DNA sequences or protein structures, disguising germ-warfare agents as benign organisms. Alternatively, plant operators could attempt to clean up a biological-warfare agent production facility after receiving notice of an on-site inspection.

The first evasion technique—using genetic engineering to disguise germ-warfare agents—is unlikely to work. Such efforts would demand a great deal of expertise and effort, and might interfere with the microbial agent's viability or ability to cause disease. Inspectors could also foil such evasive maneuvers with fairly simple countermeasures, such as devising batteries of assays directed at multiple DNA sequences or molecular markers characteristic of a given pathogen. Even though inspectors would employ only a few of these tests at a given facility, the potential violator would be unaware of which tests would be chosen and hence would have to counter all of them to ensure successful evasion—a daunting task.

The cleanup route has a better chance of success. With sufficient notice, the plant operators could disassemble biological production equipment, clean it with bleach, and then grow a new culture of non-forbidden microorganisms in the same equipment.

In practice, however, cleaning is not always complete, particularly if the process is rushed. The shorter the notification period for an on-site challenge inspection, the greater the probability that a violator will make a mistake and leave behind traces of illicit production. Indeed, molecules of microbial DNA are robust and may survive autoclaving (prolonged heating with pressurized steam, the standard method for sterilizing equipment). Thus while the incriminating microbes themselves would be destroyed, telltale DNA fragments would be left behind.

Experience with Iraq provides some confidence that sampling and analysis can uncover germ-warfare activity even if a country is determined to hide its activities. In the wake of the Gulf War, the UN Special Commission (UNSCOM) learned of a large fermentation plant called Al Hakam, situated at a barren desert location some 80 kilometers southwest of Baghdad. Iraq claimed that the facility was engaged in the legitimate production of two commercial products: single-cell protein as a supplement for animal feed, and a microbial insecticide known as *Bacillus thuringiensis* (BT).

BT bacteria normally contain tiny crystals of a protein toxin that kills insects. Yet when UNSCOM weapons inspectors took samples of BT at the facility in December 1994 and examined them under an electron microscope, the crystals were absent, indicating that the bacteria lacked insecticidal activity. Moreover, the BT product that emerged from the production line was a dry powder that was too fine for agricultural use but was in the ideal form for dispersing a biological warfare agent. These findings suggested that Iraq's cultivation of BT may have been intended as a clandestine training exercise for the production of anthrax bacteria, which grow under similar culture conditions and can be induced to form rugged spores. On the basis of this and other evidence, UNSCOM razed the Al Hakam facility in June 1996.

In recent years, UNSCOM weapons inspection teams have used medical swabs to collect material from equipment and other surfaces for laboratory analysis. Since Iraq is well aware of the power of these techniques, it is possible that one reason Baghdad moved in November to bar U.S. inspectors from UNSCOM inspection teams was a growing concern over the effectiveness of sampling and analysis. According to journalist Richard Preston, author of *The Hot Zone,* a biological weapons inspector told him that the Iraqi "minders," or escorts, "clump up in a group and get real agitated whenever we whip out our swabs."

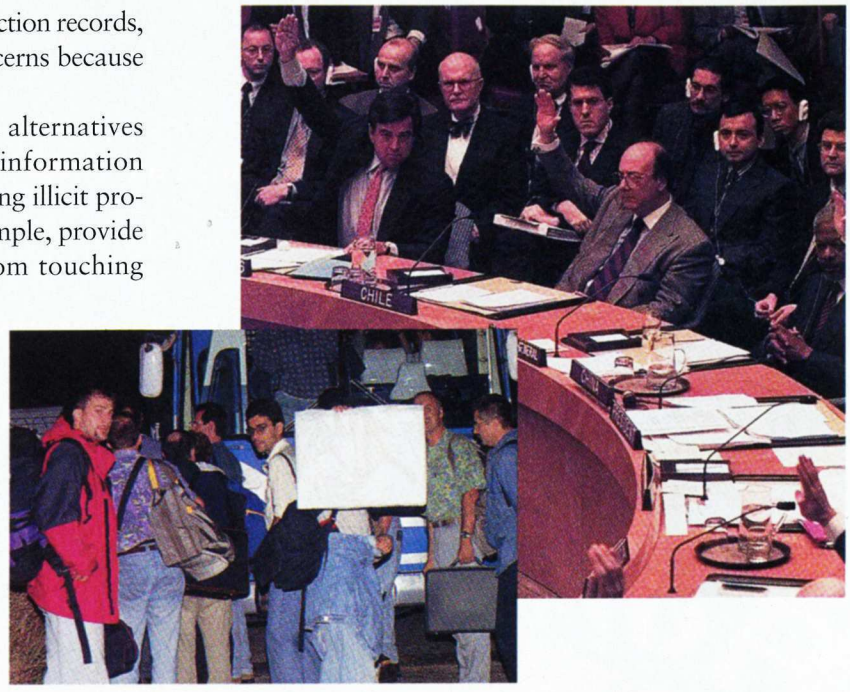
—*Jonathan B. Tucker*

cloth shrouds over items of production equipment considered proprietary, and specify where and when samples may be taken. In return for such limits on access, the inspected party must make "every reasonable effort" to provide alternative means of addressing the inspectors' compliance concerns. For example, the inspectors might ask the facility representative to lift the shroud covering a piece of equipment high enough to confirm that illegal materials are not hidden underneath, or to review the plant's production records. Failure to cooperate with such requests might lead the inspectors to suspect the facility of concealing illicit activities.

Some arms-control analysts doubt that managed access will be effective in catching BWC violators because it assumes a large degree of good faith and cooperation on the part of the inspected party. "Managed-access negotiations could create delays that, unless overcome by technology or diplomacy, might allow proliferators to dispose of incriminating evidence," contends Michael Moodie, president of the Chemical and Biological Arms Control Institute in Alexandria, Va. For example, a violator might use the managed-access negotiation as a pretext to stall the inspection long enough to eliminate most if not all traces of illicit

biological agent production. Auditing of production records, critics say, would not resolve compliance concerns because such records can be falsified.

Critics of managed access have suggested alternatives that would protect corporate proprietary information while also increasing the likelihood of detecting illicit production. The inspected facility might, for example, provide escorts for the inspectors to keep them from touching equipment and taking covert samples. In addition, inspectors could be required to remove their street clothes and don disposable coveralls, booties, head coverings, and surgical masks, all of which would be destroyed after use. The inspectors would also shower after each inspection to make sure they do not remove proprietary microorganisms on their skin. Finally, the inspected facility would have the right to demand the removal of any inspector caught taking unauthorized samples.



LEFT: UN inspectors depart Baghdad in November after Saddam Hussein ordered Americans on the team to leave. The confrontation brought Iraq's pursuit of biological weapons into the public eye.
RIGHT: Iraq's behavior brought a unanimous vote of condemnation from the UN Security Council.

As a further means of safeguarding proprietary production microorganisms, the Federation of American Scientists Working Group on Biological and Toxin Weapons Verification has proposed that personnel at an inspected facility could inactivate sampled microbes by heating them, and then partially digest the microbial genes with a special "restriction enzyme" to disrupt any confidential DNA sequences. Only then would the inspectors be allowed to verify the identity of the microbe or to screen for a list of biological-warfare agents with gene probes and immunoassays. In principle, the restriction enzyme would destroy proprietary information but leave enough characteristic DNA sequences to verify the identity of an illicit agent. This approach will need to be validated, however, both in the laboratory and in the field.

A number of government and commercial organizations are developing chip-based sensors containing an array of gene probes for detecting microbial pathogens and toxins of biological-warfare concern. Such devices might eventually be cheap enough to discard after use, like a disposable pregnancy-test kit. This approach would reassure the pharmaceutical industry, which fears that reusable analytical instruments accompanying an inspection team could, deliberately or inadvertently, remove samples containing proprietary microorganisms.

In crafting a set of on-site measures for monitoring BWC compliance, the Ad Hoc Group will need to balance costs and benefits. While technical and political constraints may circumscribe the use of sampling and analysis during on-site inspections, the mere possibility of sampling could deter potential violators by making illicit production more risky and expensive and by necessitating aggressive cleanup measures that would themselves arouse suspicion.

At the same time, devising approaches to sampling and analysis that can safeguard legitimate industrial or national-security secrets remains a major challenge. Over the next few years, however, the development of accurate but inexpensive biosensors for the identification of microbial and toxin agents may make it easier for the Ad Hoc Group to find an acceptable tradeoff between these competing objectives.

The biotech and pharmaceutical industries have a huge stake in the outcome. So far, companies have mainly played the spoiler, complaining that proposed verification methods would intrude on their proprietary rights. They need to become more constructively involved. The biological weapons threat to international security has made it imperative to institute verification measures that will fortify the BWC, converting it from a gentleman's agreement into enforceable international law. Companies that have the most to gain from biotech innovation—and the most to lose from unwanted disclosure of their trade secrets—need to help find suitable ways to allow international inspections of their production facilities without compromising the economic health of a leading U.S. industry. ■



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PHOTOS: AP/JASSIM MOHAMMED, RICHARD DREW

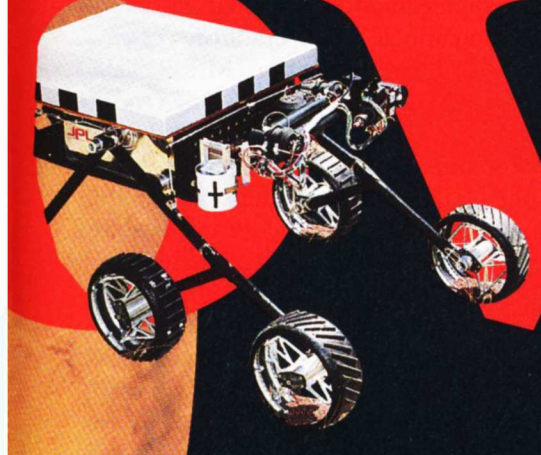
If you liked the Mars show last summer—and who didn't?—consider what made it possible and how much farther coming generations of space robots should rove.

Honey, They've Shrun



PHOTO OF MARS: US GEOLOGICAL SURVEY/PHOTO RESEARCHERS INC.; ROVER: JPL

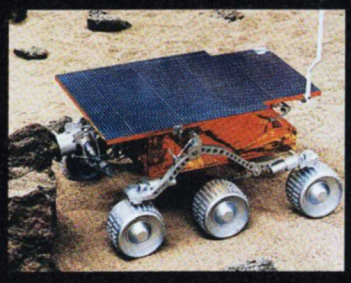
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BY ERIC SCIGLIANO

If the Nobel judges gave a prize for overachievement, a good candidate might be a six-wheeled, breadbox-sized robot named Sojourner. As robots go, the rover that explored Mars last year was a modest contraption; it traveled only about two feet a minute and performed just two simple scientific operations, photographing rocks and reading their chemical signatures. And the machine cost just $25 million, with the Pathfinder mission that carried it to Mars a bargain at $266 million, a quarter the cost of a single space-shuttle flight. But Sojourner was the Energizer Bunny of robots, the rover that just kept on roving. Officials cautiously projected that it might operate for a month on Mars; it sent back data for three. ✶ It also seized the public imagination as no space venture had since Neil Armstrong and Buzz Aldrin planted the United States flag on the moon. In the mission's first heady weeks, NASA's multiple Pathfinder World Wide Web sites recorded about 45 million hits a day. *Time* and *Newsweek* accorded Pathfinder's July 4 landing and Sojourner's subsequent debarkation simultaneous covers and the sorts of spreads usually reserved for the starts of wars or the deaths of princesses. Mattel immediately sold out the

A Rover Gallery



SOJOURNER



MRSR TESTBED



1960s ROVER CONCEPT



TOOTH

first run of its Sojourner "Mighty Wheels" toy. At a midsummer reception, Vice President Al Gore joked that he had "been replaced by Sojourner as the world's favorite robot." Had humankind ever identified so closely with a machine?

Thus did the rover and its faithful lander save NASA from the stigma of two decades of costly boondoggles, fatal disasters, and dashed expectations. The essential strategy of the reformed NASA—nix the costly, dangerous manned expeditions and let robots and other remote exploration tools do the work—had panned out.

That was just the start. NASA is now preparing succeeding generations of planetary explorers that will make Sojourner look decidedly humdrum: rovers to traverse many miles of Mars's expanses, gathering far-flung samples for transport back to Earth; "penetrators" to probe the living worlds that might lie beneath extraterrestrial rock and ice crusts; and "aerobots" to survey other planets and their moons, from Venus to Jupiter's moon Titan, and perhaps even Uranus and Neptune, from the air.

As exotic and wildly varied as these devices may seem, they all derive from the same critical change in NASA's approach to unmanned planetary exploration nearly nine years ago—"faster, cheaper, better." This change was initiated not through official NASA policy but in defiance of it, by a small group of robot-building heretics who saw a better way to go to Mars than their bosses saw and who worked covertly to make the idea possible. Appreciating the roots of that robot-building rebellion helps in understanding why planetary exploration is now taking the course it is.

ERIC SCIGLIANO, a senior editor with the Seattle Weekly *who has also written for many national publications, last year won a AAAS Science Journalism Award, one of the field's most prestigious awards.*

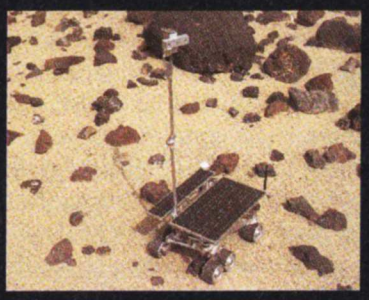
IN THE BEGINNING

The philosophy underlying "faster, cheaper, better" is "less is more." In space flight, mass equals money—lots of it—and complexity means risk. To make, say, rovers affordable and reliable, create them to be as lightweight and simple as possible—25 pounds in Sojourner's case, with a feeble but sturdy 8-bit, 1970s-level processing unit for a brain. As obvious as this strategy seems now, through the late 1980s NASA's Jet Propulsion Laboratory (JPL) focused on building something completely different: a truly formidable machine in size, range, and computational and operational ability—and cost. This Mars Rover Sampler Return (MRSR) vehicle would measure up to 8 feet long and weigh half a ton. It would be built to cruise for a year and a half in Mars's punishing cold, across 700 miles of its varied, rugged terrains, gathering samples and blazing a path for human missions. It would cost up to $10 billion.

"Then fiscal reality hit," recalls David Lavery, manager of NASA's telerobotics research program. "We realized it just wasn't going to happen."

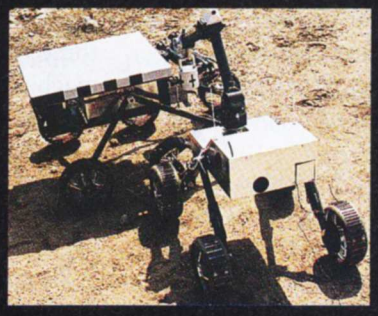
Luckily, unbeknownst to the NASA brass, an alternative waited in the back laboratories at JPL—a neglected experiment in robot automation and simplification. Even as JPL as an institution was chasing the MRSR dream to its dead end, a small group of upstart rover and another group of artifi-

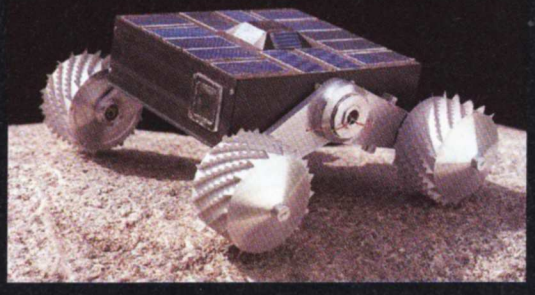
PHOTOS: JPL; DAVID MILLER; NASA



ROCKY 7

PROTOTYPES:
'01 AND '03, '05 MISSIONS





MUSES-CN
NANOROVER
PROTOTYPE

As early as the 1960s the notion of planetary rovers captured interest. NASA replaced its 1980s flirtation with the large MRSR with the idea of small, cheap machines. Tooth, which embodied simplification and autonomy, was a progenitor of 1997's Sojourner. Today Rocky 7, with a robot arm and camera mast, is being tested, while prototypes for missions after 2000 are under development. The Muses-CN nanorover, intended to explore the asteroid Nereus, is also in the works.

cial-intelligence renegades, both at JPL, had been quietly seeking solutions of their own.

The effort began in 1988, when Howard Eisen, now chief mobility engineer for JPL's rovers, left his graduate studies at MIT to work at the lab. He brought with him a particularly apt thesis project: building a one-eighth-scale model of the mighty MRSR. He found that the model, guided by an electric tether, performed much better than expected. Indeed, its five-inch wheels could climb over objects up to eight inches high. So perhaps the jumbo MRSR was unnecessary, he thought; could "a much smaller platform" negotiate Mars's rocky surface?

While NASA's Jet Propulsion Laboratory may have thought big in the 1980s, when it was working on the MRSR, the philosophy since has been "less is more." Sojourner itself could seem large if the Muses-CN and gnat robot ideas come to pass in the future.

Eisen and his JPL colleagues set out to build such a platform—working on their own in the garage of engineer (and former hot-rodder) Don Bickler. After several trials Bickler invented a six-wheeled chassis that could maintain even weight and traction on all its wheels. The engineers called it a "rocker/bogey" after its two key mechanical elements and with all due honor named the subsequent rover prototypes Rocky. "Everyone was joking over whether we'd have as many sequels as the Rocky movies," Eisen recalls. (They would.)

Midway through building the first Rocky, the rover renegades obtained lab space at JPL and gained new collaborators: a team of artificial-intelligence (AI) designers. Inspired by the "subsumption architecture" approach of MIT's AI pioneer Rodney Brooks—designing robots to operate using a hierarchy of simple reactions to stimuli—David Miller, a recent arrival at JPL's AI section, hired Brooks's student Colin Angle for a summer. At MIT Angle had created the trailblazing Genghis robot, which despite its low brainpower could autonomously perform a fairly complex function—gathering up all the coffee cups in the office. (That machine is now in the National Air and Space Museum.) At JPL, Angle built a similar robot named "Tooth" using a model-car chassis, for less than $500 in parts and $5,000 in labor.

GETTING SMALLER ALL THE TIME

	LENGTH	HEIGHT	WIDTH
MRSR TESTBED	7 FEET	6 1/2 FEET	4 1/2 FEET
SOJOURNER	2 FEET	1 FOOT	1 1/2 FEET
MUSES-CN	4 INCHES	3 INCHES	4 INCHES
GNATS	1 INCH	1 INCH	1 INCH

"My only constraint," Angle recalls, "was I couldn't spend more than $50 for each part, so it could all come out of petty cash."

Miller and his teammates saw the potential of the mechanical Rocky that Bickler's group had developed. Marrying Tooth's electronic "brain" to Rocky 3's body, they created the first autonomous rover that could operate outdoors, on actual dirt.

JPL managers were impressed, but still wedded to their big MRSR. Then Congressional members howled at its cost and that project was dead. NASA had meanwhile found funding for a single small Pathfinder lander and cast about for something to carry on it. "I said, 'We happen to have this one rover,' " recalls Miller. At last the renegades had an actual mission to work on.

But not for long. As so often happens when innovations are channeled into the mainstream, the innovators were left out in the cold. Miller and his teammates lost control of the Rocky project, and all but one of them left JPL for the private sector. Rover budgets increased, and so did timelines. Miller's group took just one-and-a-half years to progress from Tooth to the fourth-generation Rocky, but JPL then took five more years to advance to Sojourner, the sixth in the Rocky line.

JPL's Brian Wilcox, who took the helm of the microrover project after Miller, argues that this was a natural response to the challenges of making technologies "reliable enough" to work in the harsh Martian environment. Indeed, novel as it seemed to TV viewers, Pathfinder was a rather conservative mission; JPL reached back to tried-and-true command technology rather than attempting fully autonomous operation. Better safe than venturesome when the whole world is watching.

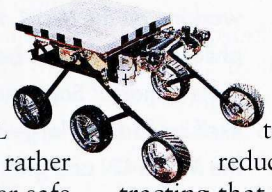
ROCKY'S KIDS

But now that Sojourner has paved the way, other planetary explorers can realize the potential it only hinted at. Rocky 7—outfitted with a robot arm and camera mast as well as a Sojourner-style chassis—is going through its paces at dry Lavic Lake in the Mojave Desert. The lakebed is an especially apt Mars analog, thanks to the aviators at the nearby Twentynine Palms Marine base; their bombing practice has left it pocked with craters, approximating the thousands that asteroids have nicked in Mars's surface.

The long-distance hiking that Rocky 7 is practicing under autonomous operation and with improved sensory and navigation systems will be critical for future Mars rovers. Sojourner crawled only a few score meters under the watchful, position-checking electronic eye of its Pathfinder mother ship. But Rocky 8, the rover-apparent for the 2001 Mars mission and its 2003 successor, will have to cover many miles, probably on rougher, older highland terrain where traces of ancient life may more likely be found. NASA wants these rovers to cache interesting samples that yet a third machine—a brawnier, more specialized "retrieval rover"—is slated to pick up in 2005 with the aid of electronic beacons left with the caches. That rover might have to haul the samples still more miles to the lander for return to Earth and the close examination that may finally settle the question of life on Mars.

Covering more ground is just one of many challenges to come for the rover makers. Others revolve around more restricted budgets. Steve Saunders, JPL's chief project scientist for the Mars 2001 mission, notes that future vehicles will have to rely on less human involvement. While the Pathfinder mission occupied up to 10 people several months after the landing with matters such as control and troubleshooting, the Mars 2001 budget allows for an operations team of about 4. The next rovers also must cost less, ride on smaller rockets, do more science (NASA is still hashing out exactly what) and run 3 times longer than Sojourner. And aside from monetary factors, they must survive an even wider range of temperatures than Sojourner did (experts figure the Martian cold finally silenced the Pathfinder mission).

Covering more ground is just one challenge for the rover makers. Others revolve around restricted budgets.



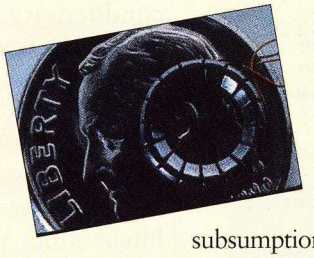
Much of the hope for meeting these challenges rests on the new graphite composites that JPL's mechanical systems division is creating. Using consistent composites throughout a rover could reduce the destructive differential cooling and contracting that now occurs when various metals are used, making the machine less vulnerable to temperature changes. And composites could shave more weight off the final payload, reducing costs. Already, a prototype "Lightweight Survivable Rover" for the '05 mission weighs only 15 pounds—two-thirds as much as Sojourner—while stretching more than one-and-a-half times as long and wide and standing nearly twice as high, a foot off the ground.

Further, this prototype's wheels collapse to a third of their extended volume and thus can pack into a smaller flight capsule, says Paul Schenker, the division's research and development leader. "We're extending that idea to the whole rover frame," he adds, vowing to make the sample-retrieval rover "truly collapsible" and hence even cheaper to send.

The greatest progress by Schenker's team has been in building arms from the lightweight composites. One arm, all composite down to its motor, weighs only about eight pounds but can lengthen to about six feet, dig a trench, lift and deposit samples, and sling a microcamera. Another,

Insect Inspiration

In the late 1980s, just as NASA's two-decade effort to build and launch a big, super-capable, boulder-hopping planetary rover was approaching its *expandio al absurdum,* Rodney Brooks, the maverick miniaturization guru of MIT's Artificial Intelligence (AI) Laboratory, was pushing robotics in the opposite direction. While other AI thinkers looked to complex human brains as models for autonomous machines, Brooks looked to insects. He noted that, skimpy though their brains are, insects get on quite nicely, performing complex functions by reacting in simple, automatic ways to various stimuli. Thus, instead of planning a route and mentally mapping a terrain, as a human would, an ant—or a robot—might follow two commands that demand much less brain power and that achieve the same end: "Go toward goal. Go around objects that get in the way."



Brooks called this hierarchic organization of simple commands "subsumption architecture," and he and his students set about putting it into practice in a now-legendary series of small robots. In 1988 he and Colin Angle took one, the still-unfinished Genghis, out for a show-and-tell at the Jet Propulsion Laboratory. Some of the space scientists were intrigued by subsumption architecture's possibilities, Brooks recalls. Angle worked that summer at JPL, building Tooth—the low-budget demonstration that eventually led to Sojourner.

Meanwhile, in a 1989 paper, "Fast, Cheap, and Out of Control," Brooks and another student, Anita Flynn, proposed all that NASA eventually undertook with Sojourner, and more: planetary missions with small, simple, mass-produced robots. "Within a few years," they suggested, "it will be possible, at modest cost, to invade a planet with millions of tiny robots"—perhaps weighing two pounds apiece.

Since then, working independently Flynn has pushed much farther into robot miniaturization, building motors into ceramic wafers about a quarter-of-an-inch long and experimenting with even smaller ceramic fabrications. Looking toward possible medical, consumer-electronic, and scientific applications of such miniaturization, Flynn predicts brashly that these could be as significant "as microchip technology in terms of changing the world."

For years Brooks continued to do NASA-funded research, pushing the agency toward what might be called "faster, smaller, dumber, and more effective" robots. He worked with JPL's Brian Wilcox on a design for half-ounce "egg" robots that might be shot off from a larger rover. These would travel by hopping on a solar-powered mechanical spring; their cameras might be programmed to look for symmetrical markings on rocks—signs of possible fossils—and to signal the main rover upon finding any of these. Brooks and Wilcox went as far as building a one-ounce prototype.



Rodney Brooks dreamt up robots with simple "brains." Intrigued by tiny robots, Anita Flynn has developed a motor smaller than a dime (left).

Brooks says he's now stepped backed from space work because he's too busy as director of the AI Lab; besides, "I'd done that for 10 years. It's good not to work on the same thing for too long." He worries about what he calls "signs of backsliding" at NASA, an abiding determination in some quarters to build what he sees as oversized, over-capable robots. But he praises the achievements of Wilcox, telerobotics manager David Lavery, and other NASA officials who uphold the less-is-more gospel—and who've lately been calling the shots.—*Eric Scigliano*

weighing two pounds, can lift several times its own weight, in part due to ultrasonic motors (so called because they whir at inaudible frequencies). Such motors maximize torque—hence traction and leverage—at very low speeds, which is just what you want for extraterrestrial uses, where high speeds increase the risk of accidents and require more information processing. Moreover, low-speed ultrasonic motors don't require gearboxes as conventional motors do to reduce their rotations to useful speeds. Eliminating the gearbox eliminates more weight; again, less is more.

By the time the ultralight rovers with boarding-house reaches are ready to fly, an even more dramatic essay in rover miniaturization may have proven itself in the first-ever landing on an asteroid. Again, necessity, in the form of payload restrictions, is the mother of design. In September 2003, the Japanese space mission known as Muses-C is due to land on the half-mile-wide, earth-crossing asteroid Nereus. The plan is to touch down at three sites (lifting off and landing again requires little power in an asteroid's low gravity), collect samples, and dispatch these to earth by January 2006 using parachutes dropped from space flights. But first Muses-C should drop off an American passenger—a rover.

When Japan's Institute of Space and Astronomical Science (ISAS) came to NASA seeking technical help on Muses-C, it offered NASA the chance to fill out the lander's unused cargo space. The Americans thought of sending a comple-

PHOTOS: BRUCE FRISCH; DONNA COVENEY/MIT

FUTURE ROVER ADVENTURES

MISSION NAME	PLANNED LAUNCH DATE	PURPOSE
MARS '01	EARLY 2001	A ROVER THAT WILL LAST FOR UP TO ONE YEAR AND CAN TRAVEL UP TO 100 KILOMETERS WILL HAVE AS ITS MAIN PURPOSE THE COLLECTION OF SAMPLES THAT IT WILL CACHE ON MARS.
MARS '03	2003	A ROVER SIMILAR TO THAT USED ON THE '01 MISSION SHOULD COLLECT SAMPLES FROM A DIFFERENT AREA OF MARS AND CACHE THEM.
MARS '05	LATE 2004	THIS MISSION'S ROVER SHOULD COLLECT MATERIAL FROM ONE OF THE TWO CACHES, DEPENDING ON WHICH AREA NASA DEEMS MORE PRODUCTIVE, AND BRING THE MATERIAL TO THE '05 LANDER FOR RETURN TO EARTH.
MUSES-C	LATE 2001	A NASA "NANOROVER" INCLUDED IN THIS JAPANESE MISSION WILL EXPLORE THE ASTEROID NEREUS, WHOSE ORBIT CROSSES THAT OF EARTH, USING A CAMERA AND A SPECTROMETER TO DETERMINE OBJECTS' CHEMICAL COMPOSITION.

ment of scientific instruments, but decided that if these were attached to the lander they would merely duplicate the Japanese effort. Better to send a rover to explore other parts of Nereus.

Just one hitch: Muses-C has only two pounds' worth of extra cargo capacity, with half needed for computer and communication equipment to enable NASA to "talk" directly with the rover. Ergo the next step in miniaturization: a one-pound "nanorover." (This is a term of art, since nanotechnology usually refers to work at the molecular level. But what else do you call a machine one-twentieth the size of a "microrover?") The nanorover's science instruments will be more sophisticated than the relatively gigantic Sojourner's: an infrared spectrometer for reading chemical signatures by infrared rays, an imaging camera with eight-position filter wheels for reading various light spectra, and perhaps an x-ray spectrometer. But the machine will have a much simpler chassis. A current prototype has only two wheels, on which it will skid and even flip over (and then right itself). On an asteroid, where impacts are glancingly light, such careening won't be the disaster it would be on a full-sized planet. In low gravity, where stopping is difficult, such movements are inevitable anyway.

An asteroid presents even more fearsome temperature challenges than Mars. Brian Wilcox, JPL's robotics group supervisor, notes that Sojourner operated only when it was warm—after its gel insulation had trapped enough heat each day. But insulating is futile on something as small as a nanorover, with its proportionally high surface area. And asteroid explorers must brace for 250-degree Celsius temperature fluctuations from day to night. Electrical components are typically rated only up to an automobile's temperature range—about 120 degrees. Finding components that can handle minus-125 degrees is a main challenge, says JPL systems engineer Rick Welch, who has worked on the nanorover. The appropriate parts tend to be CMOS—complementary metal-oxide semiconductor—electronics, which maintain conductivity and work at extremely low temperatures. The asteroid rover will be a night crawler; "during the [scorching] day, we'll just turn it off," he notes.

Wilcox sees more asteroid-hitchhiking possibilities for super-light nanorovers: For very little money "they can ride as secondary payloads with other, paying customers, such as commercial satellites," he says. A rover could kick out of orbit on a small rocket, then glide to a target on solar sails; its wheels would double as sail winches, rotating to let the sail lines out or to pull them in, thus directing the flight. Dropping to the asteroid would be no problem; a miles-high fall there would resemble an inch-high fall on earth, so an asteroid rover need not be as robust as a Mars model.

Low gravity also makes other forms of movement possible. In place of the rocker/bogey chassis, the Muses-CN ("N" for "NASA") rover will have extendable wheel struts, which will lift it up over obstacles or flip it back upright should it tip over—just as we use our arms to push ourselves up when we fall. The struts will also enable the nanorover to hop about on Nereus's surface; the trick, notes Welch, will be making sure the robot doesn't reach escape velocity—one mile an hour—and launch itself into space.

Wilcox would like to deploy such a rover to specific members of each of the solar system's 12 or so classes of asteroids and comets, completing a scientific survey that can only be done *in situ*. This could also reap the benefits of semi-mass production. He believes that, after the $28 million cost of the first nanorover, additional copies could be built for $2 million each, which he notes would be "remarkable for what's really a fully operating space vehicle."

But Muses-CN pales before the economies of scale and the saturation exploration that the next level of rover miniaturization might achieve. Call that round "micro-nanorovers": one-ounce, inch-tall prototypes modeled on the "gnat robots" propounded by Anita Flynn, CEO of the startup MicroPropulsion Corporation in Berkeley and a

former graduate student in Rodney Brooks's MIT lab. On Mars an army of such machines might scatter widely and search for water. Should they detect it, they would flip over, exposing transmitters on their bellies—and marking points on a planetary dowsing map.

Yet for all their efficiencies, narrowly focused gnats could only take exploration so far; at a certain point research must move beyond simple directives such as "find water," and researchers will need other surrogates to go places and cover distances beyond the reach of any wheeled rover, large or small. And so JPL is working on yet other, radically different planetary explorers, such as devices for digging into the innards of far-off bodies.

Going down under is essential to understanding the Jovian moon Europa, which offers the most tantalizing current prospect of extraterrestrial life. Europa appears to have a molten core—hence heat—and liquid water, which with common organic chemicals provide life's essential conditions. Trouble is, the liquid water would lie under an ice sheet that JPL's Schenker says may be up to some 60 miles thick—and because Europa is in a vacuum, is harder than ice on earth. A *cryobot*—ice robot—would have to melt through that, then release a submersible robot into the ocean below.

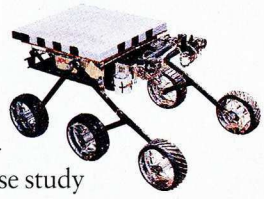
Schenker adds that Antarctica's pristine Lake Vostok, though its ice sheet is only 1.2 miles thick, offers a useful earthly analog to Europa. Hence that lake is a possible site for robotic trials. Penetrating Europa remains a matter of distant conjecture, with experts mulling over such questions as how to draw and relay enough solar energy to melt through the massive mantle of ice.

NASA is also pondering the possibility of digging into Mars's underground secrets. Again, the lure is the hope of finding life—this time below the frozen surface, where liquid water could still exist. And again, the task is forbidding: scientists estimate the external "cryosphere" could be up to six miles thick. "How do you make something to go through permafrost, rock, and sand, weigh 25 pounds, and be solar powered?" muses Welch. One point seems clear: rather than a massive, earth-style, surface-based drilling rig, the penetrating device will need to be some sort of self-contained "mole" that needs no external force to work its way down.

For the past four years JPL has worked on the idea of aerial exploration as well: aerobots, autonomous robotic balloons that could cover a much wider territory than any ground rover while producing much higher-resolution photography than satellites could. The idea isn't novel; in 1985 the Soviets and French sent a survey balloon to Venus. It performed briefly but well, bobbing upward when it approached the hot Venutian surface and the gases in its bag expanded, then downward when it hit the cold stratosphere and those gases condensed.

But the aerobots JPL is designing (and for which it will launch a test bed early this year) are much more sophisticated. Rather than floating at a constant height, they will control their altitude through valves that can release or confine the gases that give them buoyancy. Thus, explains JPL aerobot systems engineer Aaron Bachelder, they will be able to hover for some time (perhaps an hour or so) above Venus, because of the fierce heat, around 460 degrees Celsius on its surface). Then they'll retreat to the stratosphere to cool off. "Snakes"—long, dangling flexible appendages—will protect against crashes by transferring weight from the aerobot to the ground if the balloon hovers too low. The aerobots will also contain streamlined sensing and scientific instruments for up-close study of the surface. And, JPL special projects manager Jim Cutts insists, they've actually been proven not to catch on rocks in earth trials by the French. He adds, taking a page from the nanorover play book, that his crew is designing aerobots light enough—around 22 pounds—to hitch a ride with other missions.

NASA is pondering the possibility of digging into Mars's underground secrets.



NASA was figuring on Venus as the first aerobot destination, since its heat—too great for ground rovers—makes that planet an optimal choice for the balloons. And Venus's predictable winds also make it an easier place to plan routes for the devices than blustery Mars. But now that Pathfinder's triumph has made Mars fashionable, Cutts also hopes to send an aerobot to Mars in 2003—perhaps riding along with that year's rock-hunting rover.

Aerobots' prospects don't end with the two nearest planets. JPL has also sketched out aerobot missions to the Jovian moon Titan and the outer gas planets. Because those planets have much lighter atmospheres, light-gas balloons would not work on them in the way they're expected to on solid planets. And so missions to Jupiter, Saturn, Uranus, and Neptune would rely on a different, venerable technology: hot-air balloons, heated by the planets' own infrared radiation.

If the aerobots pan out, technology will have come full circle; balloons, the earliest form of airborne transport, will fly in the vanguard of planetary exploration. That's just one more indication of the diversity in approaches NASA has been employing in the eight years since it stopped pinning its hopes for investigations on a single massive Mars rover.■



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The Art of Renaissance



REVOLVING CRANE

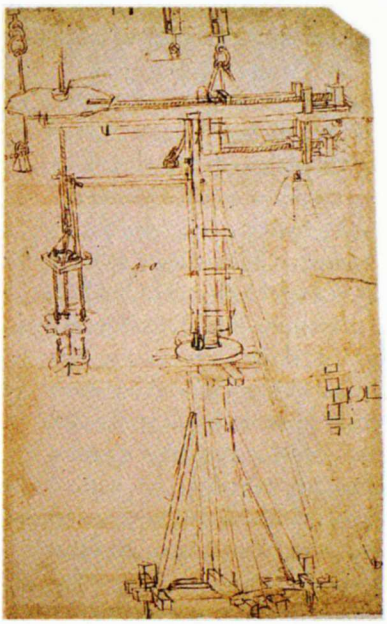
by Filippo Brunelleschi (1377-1446)

ENGINEERING

BY DAVID BJERKLIE

THERE'S something missing in our appreciation of the Renaissance, says Paolo Galluzzi, professor of the history of science at the University of Florence—something very important. While we rightly glorify this period as an extraordinary flowering of humanism and the arts, most of us have overlooked the engineering accomplishments that were just as much a part of the Renaissance as the "Mona Lisa." Granted, we marvel at Leonardo da Vinci and his technological dreams of helicopters and scuba equipment, but our instinct is to consider him a preternatural, almost freakish figure plopped down in fifteenth century Italy—the definition of that aberration, "a genius." In fact, Galluzzi explains, Leonardo represents the culmination of a century-long transformation of the technical arts and those who practiced them. To understand the Renaissance from an engineering perspective, he says, we must realize that Leonardo was no "lone visionary prophet in the desert."

As curator of the exhibit "Mechanical Marvels: Invention in the Age of Leonardo," which is on display at the Liberty Gallery in New York City until March 1, Galluzzi has provided us with the perfect opportunity to reassess the Renaissance. The exhibit focuses on the careers of four great artist-engineers of the Italian Renaissance: Filippo Brunelleschi, Mariano di Iacopo, Francesco di Giorgio, and Leonardo da Vinci. It features 50 working models of machines they devised as well as dozens of large-scale reproductions of their drawings and designs for these devices. The "mechanical marvels" include a three-speed hoist driven by oxen and capable of lifting loads of more than a ton to a height of 270 feet, a revolving crane, a mobile siege bridge, and a paddleboat, as well as such architectural masterpieces as the dome of the cathedral of Florence, 100 feet high and 165 feet across—a daring piece of engineering and construction that remains an enduring symbol of the Renaissance.

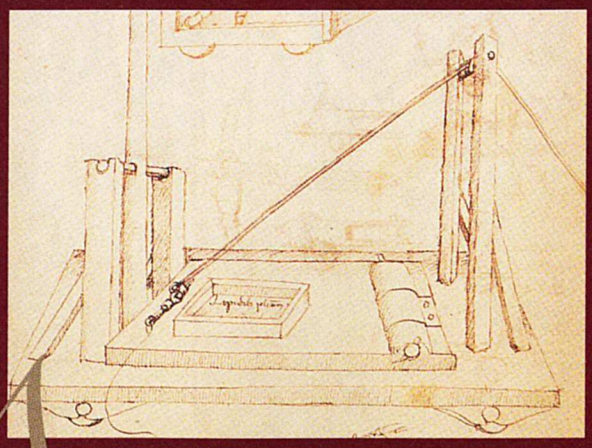


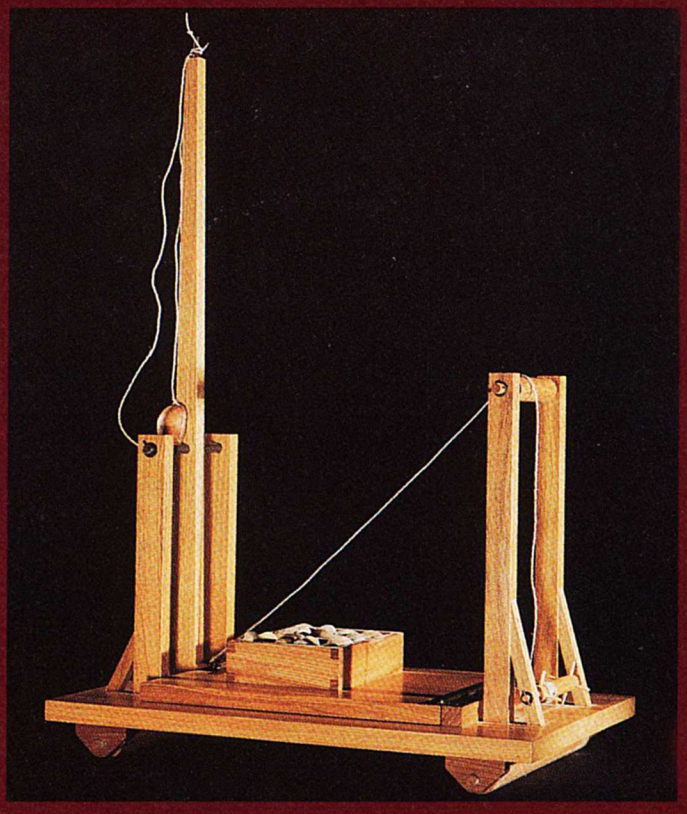
BRUNELLESCHI designed this revolving crane to build the famous dome of Santa Maria del Fiore in Florence. Leonardo da Vinci later sketched the crane to analyze its workings.

This remarkable exhibit depicts a transformation not only in the techniques available for modeling technology, but also in the profession of engineering. While the Middle Ages could claim impressive achievements and technological advances—from the great Gothic cathedrals to technologies like the heavy-wheeled plow and the horse harness and stirrup—the artisans who were responsible for these accomplishments remain anonymous and unsung. But by the height of the fifteenth century, Galluzzi explains, the artist-engineer had become "a socially prominent and respected figure, commissioned by powerful and wealthy patrons, well paid, and often regarded as one of the brightest ornaments in sovereign courts."

What initially drove this transformation was rapid growth in commerce, intense urbanization, and—perhaps most important—a climate of great rivalry among the Italian city-states. The exigencies of competition, aggression, and security during this era were "a great engine for [technological] change, which is always the rather bitter irony of war," notes Nicholas Adams, professor of the history of architecture at Vassar College and one of a number of experts who will lecture on various aspects of the Renaissance in conjunction with the exhibit. In this context, the engineer was greatly valued as a maker of military technology, says Adams. Even the young Leonardo promoted himself

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TREBUCHET

by Mariano di Iacopo (Taccola) (1382-1458?)

As part of his study of the history of military engineering, Taccola sketched this giant siege machine, designed in the Middle Ages to hurl heavy stones at the walls of enemy fortresses. The scale model, like others shown on these pages, was built by contemporary artisans using traditional methods and materials for the exhibit "Mechanical Marvels: Invention in the Age of Leonardo."

DAVID BJERKLIE is a senior science writer at Time *magazine.*

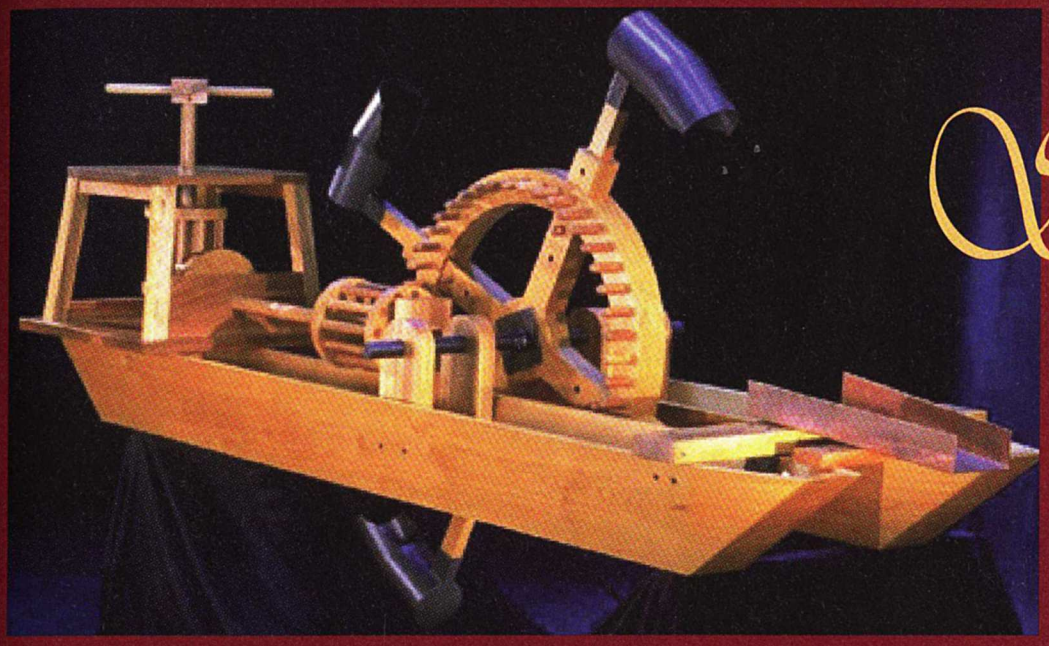
to potential employers by boasting of his abilities as a military engineer and designer of siege apparatus.

As the artist-engineer grew in social prominence, he sought to present himself as a learned member of the court, a philosopher, and perhaps most important, an author of texts. The Renaissance artist-engineers patterned themselves on such celebrated figures as Vitruvius, a Roman engineer and architect of the first century B.C. who codified the principles of architecture in a monumental work titled *De architectura*; they sprinkled their works with quotations (or more often, says Galluzzi, misquotations) from classical sources. But unlike Vitruvius and other classical scholars, whose treatises were long on text but short on illustration, the Renaissance engineers integrated text and images in a revolutionary manner. In doing so, they developed many far-reaching innovations in graphic representation.

The artists-engineers of the Renaissance discovered the laws of perspective and the techniques of cutaway, exploded, and rotating views. They pioneered the thinking sketch, the working drawing. As Eugene Ferguson wrote in *Engineering and the Mind's Eye*, this "series of fundamental graphic inventions . . . greatly enhanced the precision with which a vision in one person's mind might be conveyed by material means—drawings—across space and time to another person's mind." This crucial development both enabled and reflected the evolution of engineering from a workshop-based, case-by-case approach to a discipline rooted in principle and theory.

Prior to the Renaissance, design and construction were based almost solely on scale models fashioned by the hands of artisans. "Models are great," Adams says, "because they show you in three dimensions how things are going to look and work." Drawing, however, is quicker, cheaper, and more portable; it allows ideas to be transmitted across distances. "What's interesting," he adds, "is that the intellectual and conceptual effort that drawing involves becomes the engine for further development. It becomes a means of invention, of innovation."

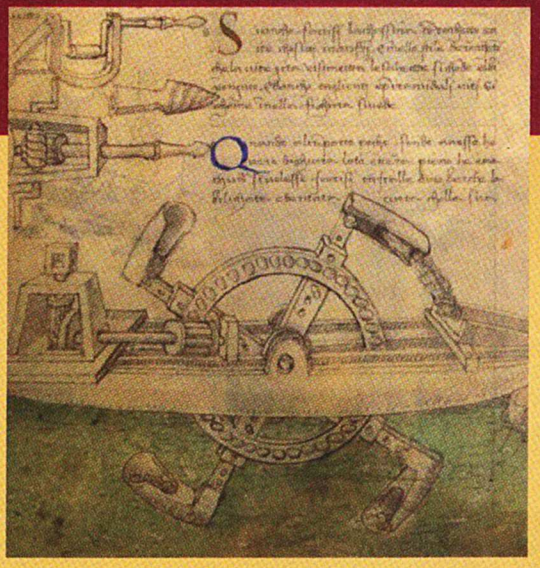
In the careers of the four artist-engineers featured in "Mechanical Marvels," we can see how technical drawing evolved hand in hand with the changing role of the engineer. Filippo Brunelleschi (1377-1446) was the first Renaissance builder to break from the engineer's traditional and largely anonymous role as a provider of technical services. Best known today as the man who designed and built the dome of Santa Maria del Fiore, he earned greater renown among his fellow engineers for the construction



Siena's artist-engineers avidly explored hydraulic mechanisms—a fascination born of the region's chronic water shortage. Francesco designed this mud extractor to keep shallow waterways navigable. Its adjustable arms permitted the vessel to operate at varying depths.

MUD EXTRACTOR

by Francesco di Giorgio (1439-1501)

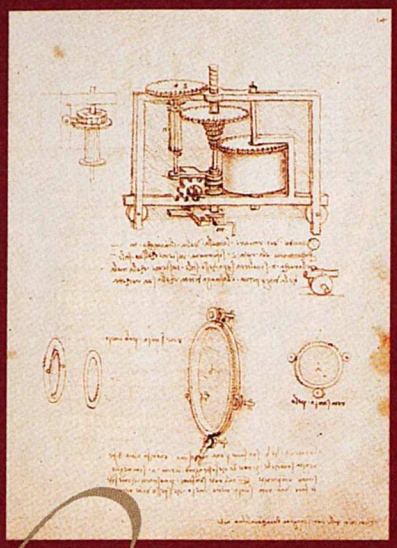


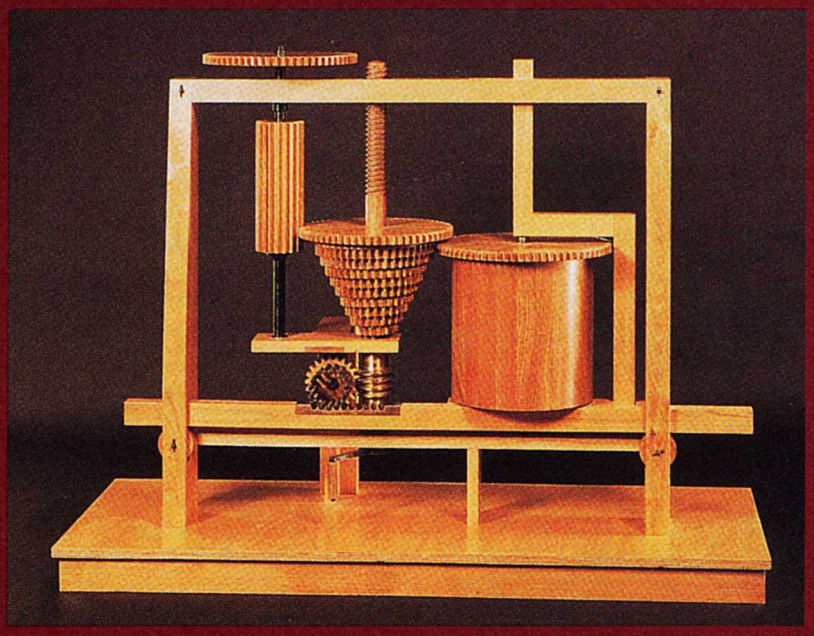
machines he invented to build it, such as the revolving crane shown on page 54. The ambitious scale and complex nature of the construction projects that Brunelleschi undertook certainly must have required him to draw, but none of his drawings survive. Like his contemporaries, he may have destroyed them in accordance with the code of secrecy typical of medieval guilds. Nonetheless, the Florentine is credited, according to Eugene Ferguson, with discovering the mathematical laws of perspective and producing the first demonstrations of these principles around 1425. The rules he devised were later codified and published, providing a foundation for other artist-engineers who followed him.

Brunelleschi saw himself as a craftsman, not an author. It is in the work of two engineers who followed, Mariano di Iacopo (1382-1458?), known as Taccola, and Francesco di Giorgio (1439-1501), that we see the first big steps in the development of the engineer as author and illustrator. These engineers, both of Siena, were deeply engaged in a variety of the city's ambitious military, construction, and hydraulic projects. But they also set out to distinguish themselves as authors, compiling technical writings with innovative illustrations. "The artist-engineers of Siena grasped the tremendous interpretative and expository potential of graphics," Galluzzi says, and they consciously devised ways to turn it into a powerful tool in their writings.

Taccola set out to recover the technical wisdom of antiquity. He discovered that often the best way to understand a difficult text was to make a visual translation of it. The techniques of the cutaway and exploded views (still indispensable for assembly, operating, and repair manuals) originated in his notebooks. He did not stop at explicating the ancients, however, but went on to fill several volumes with drawings of machines and inventions, ranging from military weapons such as trebuchets (see facing page) and hull-piercing devices to advanced fishing technology and waterwheels designed to capture the energy of the tides—a compendium that blends engineering dreams and a search for practical solutions, Galluzzi observes. And in a touch that expresses the continuity of the Sienese tradition, he notes, the final pages of one of Taccola's manuscripts were completed in the hand of Francesco di Giorgio.

Francesco's own writings make clear that he





SPRING MOTOR

by Leonardo da Vinci (1453-1519)

Leonardo's spring motor is a complex device designed to regulate the force of a spring concealed within the cylindrical drum. The machine, probably intended to control the movement of large clocks, combines a variety of mechanisms including a toothed wheel, worm screw, cone-shaped gear, and rack.

studied Taccola's texts closely. The so-called Vatican *codicetto*, a tiny notebook filled with notes and drawings modeled on Taccola's manuscripts, illustrates the learning process that characterized the Renaissance workshop: observation, imitation, and refinement of a predecessor's work. The *codicetto* was obviously "a compendium for personal use," Galluzzi observes, "a pocket notebook whose only unusual feature is the parchment sheets, which would normally have been quite extravagant for such a purpose." Then again, Francesco probably used—and reused—these pages for a decade or more.

Like Taccola, Francesco undertook an ambitious project of illustrating a vast catalogue of machines, the *Trattato di architettura*. What was distinctive in Francesco's approach, however, was that he tried to order these machines according to general rules. He categorized devices as either mills, pumps, pulling and lifting machines, or wagons, and provided commentary on materials, construction, specific applications, and even hints on ways to reduce wear and tear. Moreover, within a basic category, such as mills, Francesco would present as subcategories water mills, windmills, human- and animal-powered mills.

What was significant about this mechanical taxonomy, explains Galluzzi, was that it represented "the gradual emergence of criteria for describing machines by type and category based on the identification of common principles." Based on his study of these devices, Francesco was able to design new machines far more advanced in mechanical design than Taccola's, such as the mud extractor shown on page 57.

It was Leonardo da Vinci (1452-1519), of course, who initiated the most ambitious expansion in the role of the artist-engineer, progressing from astute observer to inventor to theoretician. In his notebooks, which combined text and illustration, we see what are truly "thought experiments" in all kinds of areas, Galluzzi says. He analyzed, in almost anatomical detail, the "elements of machines" and combined them in innovative ways, such as in the complex spring motor (above). Drawing played a key role in this effort: it allowed Leonardo skillfully to dissect mechanical devices and reassemble them using the full range of illustration techniques he had mastered. His drawing of Brunelleschi's revolving crane (page 55) is one such example—in fact, the model currently on exhibit was built according to the specifications found in Leonardo's sketches.

As his interests extended to other subjects—optics, hydrology, geology, and ultimately the human body—his studies were informed by his fascination with machines. For instance, Leonardo presents the human body, says Galluzzi, "as a remarkable ensemble of mechanical

devices." He sketches muscles, joints, and the motions of limbs in terms of wedges, axles, fulcrums, levers, and counterlevers—"the outcome," Galluzzi notes, "of a bold attempt at unifying nature under a small number of universal laws."

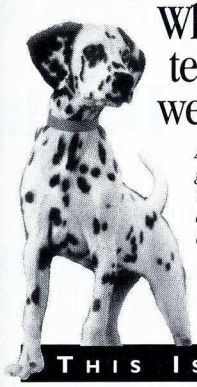
And again it is drawing that provides a new dimension to these investigations. In Leonardo's view, drawing was indispensable if a machine or body or phenomenon was to be truly and wholly known. "O writer, with what letters will you describe with such perfection all that is depicted here in drawing?" asked Leonardo; " . . . don't try to convey to the ears those things that pertain to the eyes, because the painter will be vastly better at it than you. . . . Therefore it is necessary to draw as well as to describe."

What the Renaissance artist-engineers devised, Adams explains, was a way of working through the medium of drawing. "Leonardo comments on his copy of Francesco di Giorgio's treatise," he says, "and Francesco makes notes on his copy of Taccola. There is an internal commentary on drawing that is taking place, an internal discourse. There was nothing like this in earlier periods. What we have in the Renaissance are drawings about ideas, drawings about experiments."

Leonardo was the grand master of this form of experimentation, Adams adds: "He just drew and drew and drew and created more and more ideas. And though relatively few of these ideas were actually realized, what's important is that he kept developing the language. And it's this language that becomes the basis for scientific experimentation and technological development in the centuries that follow."

Today we take for granted the scientist's and engineer's notebook filled with questions, notes, quotes, drawings, scribbles, and erasures. But it was the Renaissance artist-engineers who invented the form. We see in their texts and drawings the complex interplay between practice and theory, and the overlapping aims of art, science, and technology. "Depicting nature, understanding nature, and modifying nature were all intertwined," says George Bugliarello, former president of Polytechnic University, "and artists, engineers, and scientists alike were all engaged essentially as researchers." In the work of the fifteenth century artist-engineer, he says, it is difficult to determine where the engineering begins and the science or art ends.

The Renaissance represented a rejection of constraints and an embrace of artistry that contemporary engineers would do well to emulate. As Eugene Ferguson observed in *Engineering and the Mind's Eye*, "The conversion of an idea to an artifact is a complex and subtle process that will always be far closer to art than to science." What "Invention in the Age of Leonardo" presents so strikingly is a reminder of how inspiring the blurring of those boundaries can be. ■



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LONGVIEW

BY AMY BRUCKMAN

Digital Perfection

"COMPUTER class is definitely the best!" says Keith. The 10-year-old and his classmates are making interactive storybooks. Keith wants to make a story about Bart Simpson, and starts surfing the Web for a suitable picture.

At the next computer, Myracle and Kim are browsing through a collection of clip art, looking for a dolphin. It's not under mammals, so they look under fishes—but again find nothing. After 15 minutes, they discover an image under the category "things in the sea." The picture is too big. They try to scale it to size, but that makes the lines look fuzzy. Another 20 minutes pass, and the end of class draws near. "Why don't you just draw your own dolphin?" I ask. They glare at me incredulously: "No way! We want it to look *nice!*"

On their desk, Myracle and Kim have a small stack of crayon drawings. Their teacher has asked them to plan the storybooks on paper before sitting down at the computer. Their drawings are messy but expressive: the dolphin is going to overcome her shyness to make friends with a giant clam. On paper, it seems, it's OK for a ten-year-old's art to look like it was done by a kid. On the computer, that's another story. They want their interactive storybook to look like the flashy commercial software they see.

What is it about the computer that makes these kids so critical of their own work? They see professional-quality art on paper all the time, yet they're not shy of drawing with crayons. Exactly why is unclear, but on the computer, the cultural permission for a ten-year-old to be a ten-year-old erodes. Children hold themselves to impossibly high standards.

A year ago I gave my friend's daughter, Lisa, some drawing software for her eighth birthday. The program came with a great collection of stamps—professionally drawn little pictures that you can put all over your page. There are dozens of kinds of birds and flowers. And there are bricks, roofing tiles, and window panes so you can stamp out a house from premade pieces. Lisa uses a flurry of stamps, all over the screen. She rotates them, stretches them, and scrambles them around—but she never draws anything of her own. When I suggest that she try, she gives me the same disbelieving look I got from Myracle and Kim.



Computer-using kids are extraordinarily self-critical of their own handiwork, holding themselves to impossibly high standards.

The computer is not a very good tool for freehand drawing. It's no wonder that kids don't like to use the mouse as a pen. But that's not the whole story. Working on the computer, kids tend to compare their drawings to those they see in professional software, and their own work usually doesn't measure up.

It's a shame the computer seems to discourage the development of drawing skills. But I have a larger concern. Children nowadays are under constant pressure to excel, as they are whisked by their parents from one after-school activity to another—most of them competitive in nature. Kids struggle to make the gymnastics team, to score that soccer goal, to earn the next merit badge. Myracle and Kim feel that no drawing they could do on the computer could possibly live up to their own standards, so they aren't even willing to try. Could the computer be intensifying this pressure—fostering a generation of people who will never be able to live up to their own expectations for themselves?

MIT professor Sherry Turkle has written that the computer often functions as a kind of mirror—or, more precisely, as a Rorschach test: what we see in it tells us something about ourselves.

ILLUSTRATION: TODD GRAVELINE

Today's overstressed children look in that mirror and see themselves as lacking. Their own work isn't good enough and never could be.

If the computer is functioning as a mirror, then the solution is not to get different software, nor to get rid of computers. Rather, the solution is to put less pressure on our kids. To give them time just to hang out. To encourage their interests, but not expect them to be perfect. To let them get less-than-perfect grades without being labeled "learning disabled."

For children having difficulty learning to write, the computer's perfection can be a great relief. Many kids look at their own handwritten letters and grimace—"I can't do this!" Typed on a computer, their writing looks more real. This helps some kids to relax and decide to give it a try. If they can make letters that look neat and adult-like on the computer, then they're willing to begin to learn to write. Their handwriting may never improve, but that matters less and less; even elementary school students now often type assignments. Indeed, while the computer tends to cramp students' ability to draw, it gives many of them a tremendous boost in their ability to express themselves in words.

Computers don't just make us do things faster. They change what we do, how we do it, what we want to do, and how we feel about what we're doing. Ultimately, they change who we are.

Class ends. Myracle and Kim throw away their dolphin. Despite their attempts to mold the pre-made digital image into something suitable for their storybook, the result still just doesn't look right. Keith still hasn't found the perfect Bart Simpson. They'll all have to start over next week. ■

AMY BRUCKMAN is an assistant professor at Georgia Tech's College of Computing, where she studies virtual communities and education. Her e-mail address is asb@cc.gatech.edu.

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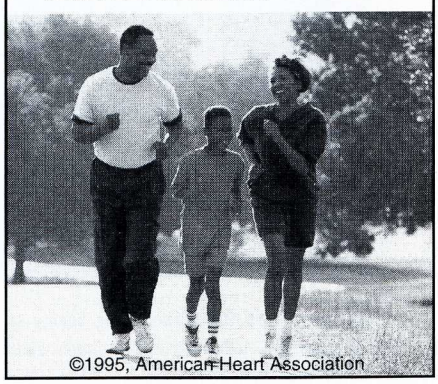
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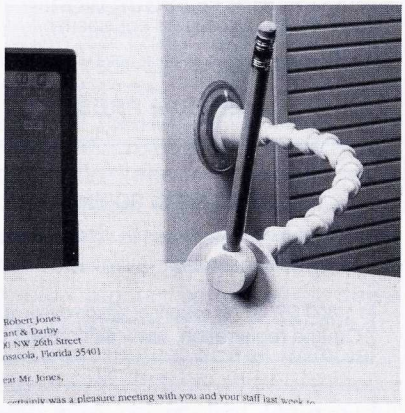
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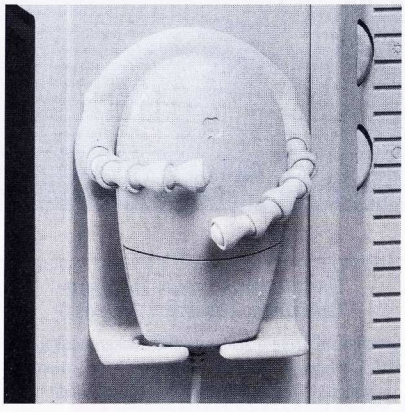
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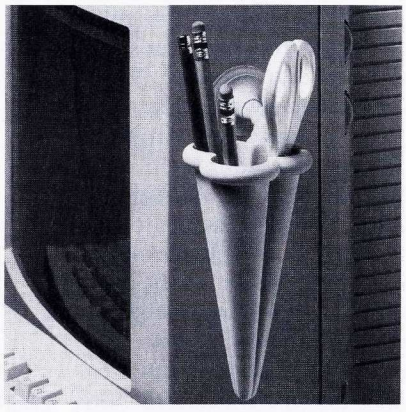
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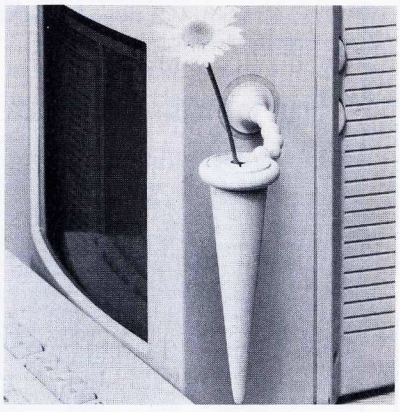
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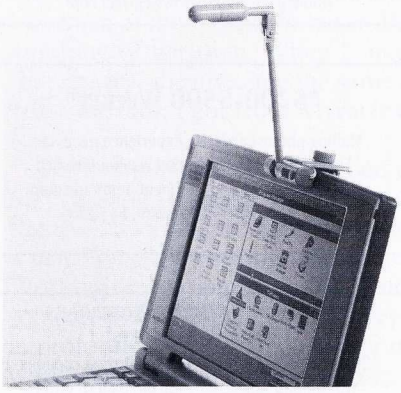
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A Tale of Tech Cities

The upbeat spirit of renewal that prevails in urban areas around the nation comes from the application of new technology and from the dynamism of technology companies.



BENNETT HARRISON

CITIES across the country are marrying technology and urban revitalization to an extent that the old political bosses and real-estate developers could never have imagined in their wildest dreams.

In San Francisco, planners are putting up "smart" office buildings and rewiring school rooms to make them computer friendly. New York City is replacing brooms, dust pans, and scrub mops for its welfare-to-work trainees with modern street and subway cleaning equipment—and teaching them how to use it. Developers in Milwaukee, Cleveland, and Seattle are setting up local area networks to link small manufacturers and service providers with bigger companies to engage in computer-assisted joint product design and to better monitor quality.

In one meeting after another with city councils, economic development departments, and corporate executives, I am hearing story after story about a technology-driven "new urbanism." For example, geographic information system (GIS) software is dramatically transforming even such staples of the typical mayor's responsibilities as management of the police force. GIS software helps track the location and spread of incidents of crime, down to recording at which fire hydrant or in which alleyway a suspect was last spotted or where recovered weapons were stashed. The cleanup and restoration of rivers and lakes, which has contributed enormously to the growth of the lucrative tourist industry, would be impossible without the advent of commercially affordable chemical solvents and processing machinery unknown a decade ago.

Technology, in short, is radically improving the quality of urban living, and not only by the direct application of innovations. The design, production, testing, and marketing of these new processes, products, and systems has itself become a growth industry that is turning around the fortunes of once-ailing cities and regions. The companies—some of them startups, some established lions in their sectors—create jobs, add to the tax base, and contribute to the upbeat spirit of renewal that even a casual visitor encounters these days in so many places.

Moreover, the presence of these high-tech players is shoring up the sagging fortunes of the typical city's older industries—a feat once thought next to impossible. I have toured older factories and warehouses that are becoming customers for the systems and services that the new technology firms are selling. Where resurrection of older operations is uneconomical, savvy architects are seeing opportunities to buy up the properties and convert them to company headquarters, labs, or residential quarters for the software engineers and analysts who are the lifeblood of the revival.

If there is a downside to all this good news, it is that the benefits of the new urbanism are not reaching all residents equally. Workers of color, in particular, continue to experience higher rates of unemployment, underemployment, and poverty. And it's not just a matter of who does or does not have the requisite education and skill. Yes, the most poorly schooled residents will have a hard time in the new economy.

But the conventional wisdom is off the mark here. Economists David Howell and Edward Wolff have used data from the U.S. Bureau of Labor Statistics to show that plenty of good jobs flowing directly or indirectly from these technical developments have quite modest skill requirements—from hospital lab technician to diesel truck mechanic to telephone/modem cable installer. Moreover, consortia of neighborhood-based organizations and community colleges are getting steadily better and more competent at training the residents of even the toughest neighborhoods to get and hold jobs in the new economy.

The new urbanism of the mid-to-late 1990s owes part of its good fortune to the long-lasting national economic expansion, now into its seventh year. But only part. Creative government has surely made a difference, as has a new spirit of collaboration and civic-mindedness among a new generation of managers in the private sector.

Most of all, to a far greater extent than I (along with those old big city machine politicians) might once have imagined, an amazing array of new technologies, technologists, and clever companies may well be ushering in a new era—one of urban economic growth and development that just might, as they say in show business, have legs. ■

BENNETT HARRISON teaches economics and urban policy at the New School for Social Research in New York. His next book, Workforce Development Networks, *will be published next month by Sage. His e-mail address is benh@tiac.net.*

PHOTO: L. BARRY HETHERINGTON

Finding Common Ground

The disdain with which many engineers regard politicians is misplaced; central to both crafts is a continual need to compromise.



SAMUEL C. FLORMAN

THE year 1997 should be recorded in U.S. history as the Year of Compromise.

In a momentous decision announced last summer, the Democratic administration and the Republican leaders of Congress agreed to balance the budget by means of granting mutual concessions. President Clinton acceded to conservative demands for reduction in government spending and unprecedented reforms to welfare legislation. The Republicans approved increases in spending for education, as well as other costly programs they had sworn to oppose. Although each side was accused by party supporters of "selling out" in matters of hallowed principle, the public, by and large, seemed relieved that the harrowing gridlock of recent years was to be averted.

I'm intrigued by the parallels between this historic agreement and the practice of engineering. This is not an obvious association. Most engineers, after all, have a devotion to principle that has been nurtured in a professional environment where being right is essential, and abiding by standards is fundamental. And some aspects of political life are totally antithetical to engineering mores—for example, promising something that you know you cannot deliver.

The political ability to compromise, however, is closely allied to crucial aspects of the engineering method. The disdain with which many engineers commonly regard politicians is misplaced—or at least not as well thought through as it might be.

Look at how our politicians cope with the directives of a selfish, fickle, and essentially irrational, electorate. The American people call upon President Clinton to end the liberal, do-good spending of the past, balance the budget, reduce taxes, and do away with government interference. Incidentally, say the people, please be sure to maintain our entitlements, see that the needy do not suffer, put an end to crime, and generally guarantee that the good things that are done by government are maintained at the level to which we have become accustomed. Members of Congress receive similar contradictory messages, along with warnings about the consequences of failing to deliver the impossible.

Do the politicians say, as they have every right to say: Hey, are you kidding? No, they do not. They consider all the various demands, appraise the pushes and pulls of political and economic reality, and try to achieve agreement by compromise. We are a nation of accommodators. Yes, we admire statements of principle, and adherence to principle. Each of us hopes that gradual "progress"—as we interpret the word—can be achieved by means of persuasive debate. But in the short term, compromise is the only way to proceed, short of social disorder.

The engineering process is amazingly analogous. The public says to its engineers: give us products that are functional, durable, delightful to use, and most important, eminently affordable for most of our citizens. Oh, incidentally, make these products safe, nonpolluting, attractive, and while you're at it, socially beneficial. And please take care to build your factories and power plants where we won't see, hear, or smell them.

How do we engineers respond? Do we say: You must be kidding; you're asking for the impossible? No we do not. We may grumble a bit, but then we do exactly what the politicians do; we compromise. We call it making trade-offs. Amid the socio-economic complexities of our age, good engineering demands no less.

In both engineering and politics, to be sure, there are certain fundamental responsibilities that cannot be abdicated. Engineers are committed to protecting public safety; governmental officials are sworn to maintain national security and public order and to keep people from starving in the streets. But beyond a few such basics, the greater morality demands that we settle our differences—after attempting persuasion—by granting mutual concessions.

Unhappily, while engineers have become adept at making judicious trade-offs in their work, they have not shown similar political skills in arranging their organizational affairs. The history of engineering societies in the United States, for example, is replete with feuds, schisms, and defections, both personal and doctrinal in origin. I believe that many engineering initiatives—such as seeking support for technology education and attempting to improve the public image of the profession—have been impeded by a failure of engineers to work together in harmony.

I propose that engineers try approaching human relations with a touch of the delicate diplomacy they have learned to apply to the complex and demanding technology of our times. Politics in engineering. It sounds strange, but it could lead to good things. ■

SAMUEL C. FLORMAN (scf97@aol. com), a civil engineer, is the author of The Existential Pleasures of Engineering, *recently reissued in a new edition. His latest book is* The Introspective Engineer *(St. Martin's Press).*

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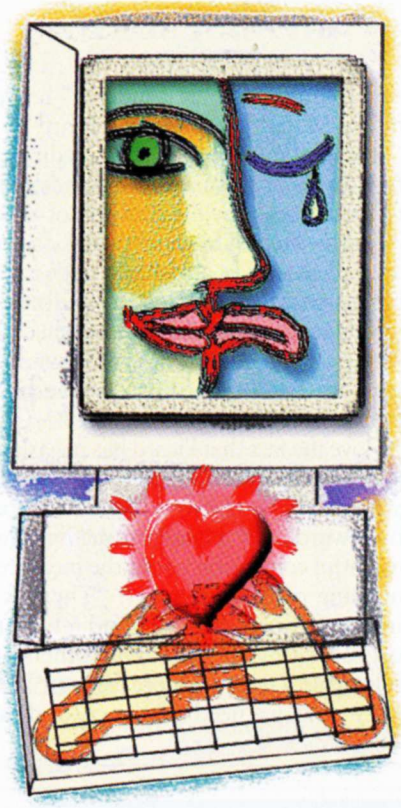
Reviews

BOOKS

THINKING ABOUT EMOTIONAL MACHINES

Affective Computing
by Rosalind Picard
The MIT Press, $27.50

BY NORMAN WEINSTEIN



I was trying to summarize Rosalind Picard's ideas in *Affective Computing* while talking with a technician working on my home computer, a machine as fond of crashes as any Indianapolis 500 grandstander. "What's that book you're reading?" he asked. *"Affective Computing,"* was my gruff, short-tempered reply. "That's a good one," he said. "You're reading about effective computing and you can't get your computer to work!" I let the misunderstanding remain, realizing that "effective" and "affective" also have similar meanings for Picard, an associate professor of media technology at the MIT Media Laboratory. Her book is a revolutionary proposal to make computing more effective by factoring in emotions.

While Picard's title might suggest a study centering upon our emotional responses to computing, her vision actually encompasses an even more daring and unsettling theme: the possibility that computers can become capable of responding intelligently to the emotions of their users. As Picard writes in her preface: "I have come to the conclusion that if we want computers to be genuinely intelligent, to adapt to us, and to interact naturally with us, then they will need the ability to recognize and express emotions, to have emotions, and to have what has been called 'emotional intelligence.'"

What sounds like a totally preposterous premise—feeling computers sounds like a cyber-age update of the Tin Man in *The Wizard of Oz* (a machine retrofitted with a "heart")—becomes an increasingly plausible reality as the reader follows Picard's captivating (if labyrinthine) course of reasoning. While refusing to narrowly define "feelings" or approve of any single psychological theory regarding their meaning in terms of cognition and personality, Picard focuses upon the physical manifestations of feelings (facial expression, vocal intonation, pupil dilation) and considers how through sensing devices (gloves, masks, sensor-laden jewelry and clothing) computers might receive and usefully act upon input about user emotionality. That input could be interpreted through programs demonstrating reasoned responses to what these biological patterns might imply about the user's computing needs. In the chapter entitled "Applications of Affective Computers," Picard lists a range of possible practical uses, including adding emotional inflection to synthesized speech programs for the disabled, and educational software capable of recognizing student frustration with technology and consequently altering its patterns of presentation.

It needs to be emphasized, and Picard does remind her readers, that affective computing is in its infancy. It is precisely because the feasibility of affective-sensitive technology is still so unknown that Picard's book seems to exist in a curious zone somewhere between science and science fiction. The text is divided into two parts, underscoring the book's hybrid identity. Part one is a compelling (though somewhat rambling) account of how and why Picard developed this approach. Part two, which is far less readable than the first, particularly for nonscientists, describes actual and possible affective computer designs, leaving me with the impression that many years will pass before affective computing will be substantially realized.

There are a dizzying number of technical issues involved. Biosensing devices to communicate the physical consequences of user emotional responses are currently readily available. The dicey aspects of the technology seem to turn upon the issue of how to program computers to process emotional data consistently and intelligently. Picard seems to rely upon the conceptual model of emotion offered by Daniel Goleman in *Emotional Intelligence* (Bantam, 1995): emotions are events we can reason about. Humans can think about feelings in order to chart desirable courses of action, and Picard convincingly demonstrates that computers can also be designed to think about feelings and how to rationally act in light of them.

Where Picard transitions from science to science fiction is when she contemplates computers possessing their own emotional intelligence independently of their human operators. In her mind-boggling contribution to David G. Stork's *HAL's Legacy: 2001's Computer as Dream and Reality* (MIT Press, 1997), she raises a usefully disturbing question: "Can we create computers that will recognize and express affect, feel empathy, exhibit creativity and intelligent problem solving, and never bring about harm through their emotional reactions?"

But even if all of the technical obstacles surrounding affective computing can be overcome, the deep question surround-

ILLUSTRATION: SUSAN LEVAN

ing affective technology might not pivot on a "can" but a "should." Should we look toward machinery to better understand what to do with the feelings in our hearts? A pessimistic image comes to mind as the question is posed. The near-human HAL in the "2001" film definitely has a Frankenstein-like undercurrent: HAL kills the spaceship's human crew with nary a twang of conscience.

But let's return to the image of the Tin Man in *The Wizard of Oz*, which might be a better metaphor for Picard's vision than HAL. Remember the Wizard does some surgery on the Tin Man, cuts a space through his armor, and inserts a silk heart filled with sawdust. "Isn't it a beauty?" asks the Wizard. And in two sentences, the author, L. Frank Baum, cuts to the chase, anticipating by nearly a century debates about how to create (and if we should create) humane and humanizing technologies: "It is indeed!" replies the Tin Man, "But is it a kind heart?"

It is very much to Picard's credit that she is aware of the many ethical and moral dilemmas raised by the prospect of affective technology. This book really doesn't attempt to deal in any depth with those dimensions. Rather it is a groundbreaking preface to a plausible direction in computing design, one that will inevitably open up Pandora's boxes beyond the domain of technological invention.

I love the fact that Picard has me asking questions like "Can my computer be programmed to demonstrate genuine empathy toward me?" Equally attractive is her insightful conclusion about the measured meaning of her discovery: "There is a time to express emotion, and a time to forbear; a time to sense what others are feeling and a time to ignore feelings. . . . In every time, we need a balance, and this balance is missing in computing. Designers of future computing can continue with the development of computers that ignore emotions . . . or they can take the risk of making machines that recognize emotions, communicate them, and 'have' them, at least in the ways in which emotions aid in intelligent interaction and decision making."

The fact that Picard is taking the risk of leaping into terra incognita is a reason to rejoice. There is deep sensibility married to technical savvy throughout these pages, and I trust that Picard would have given HAL some model of a feeling brain, the Tin Man a good heart, and will give, if possible, future affective computers something akin to a noble soul.■

NORMAN WEINSTEIN is a widely published poet and critic who writes about technology for Educom Review *and* Wired *magazine.*

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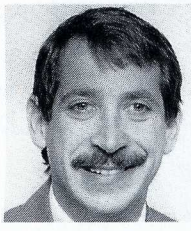
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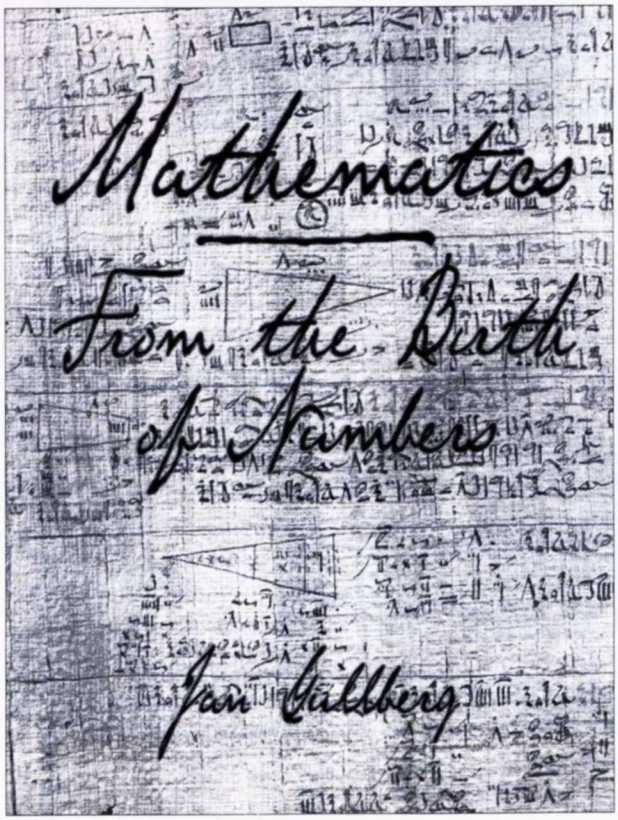


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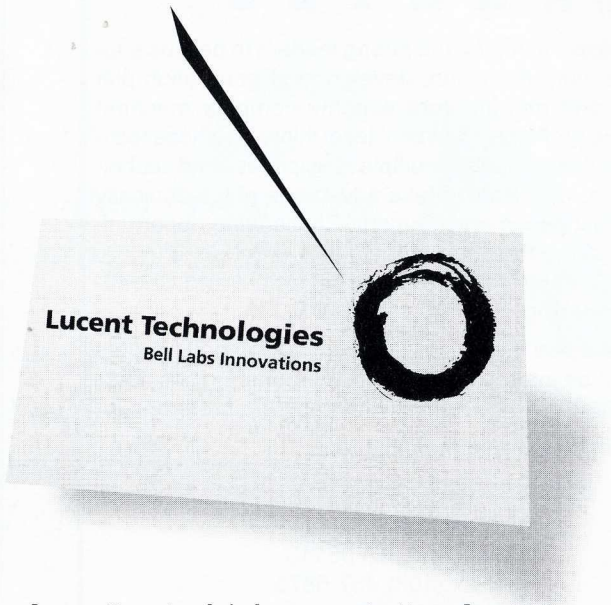
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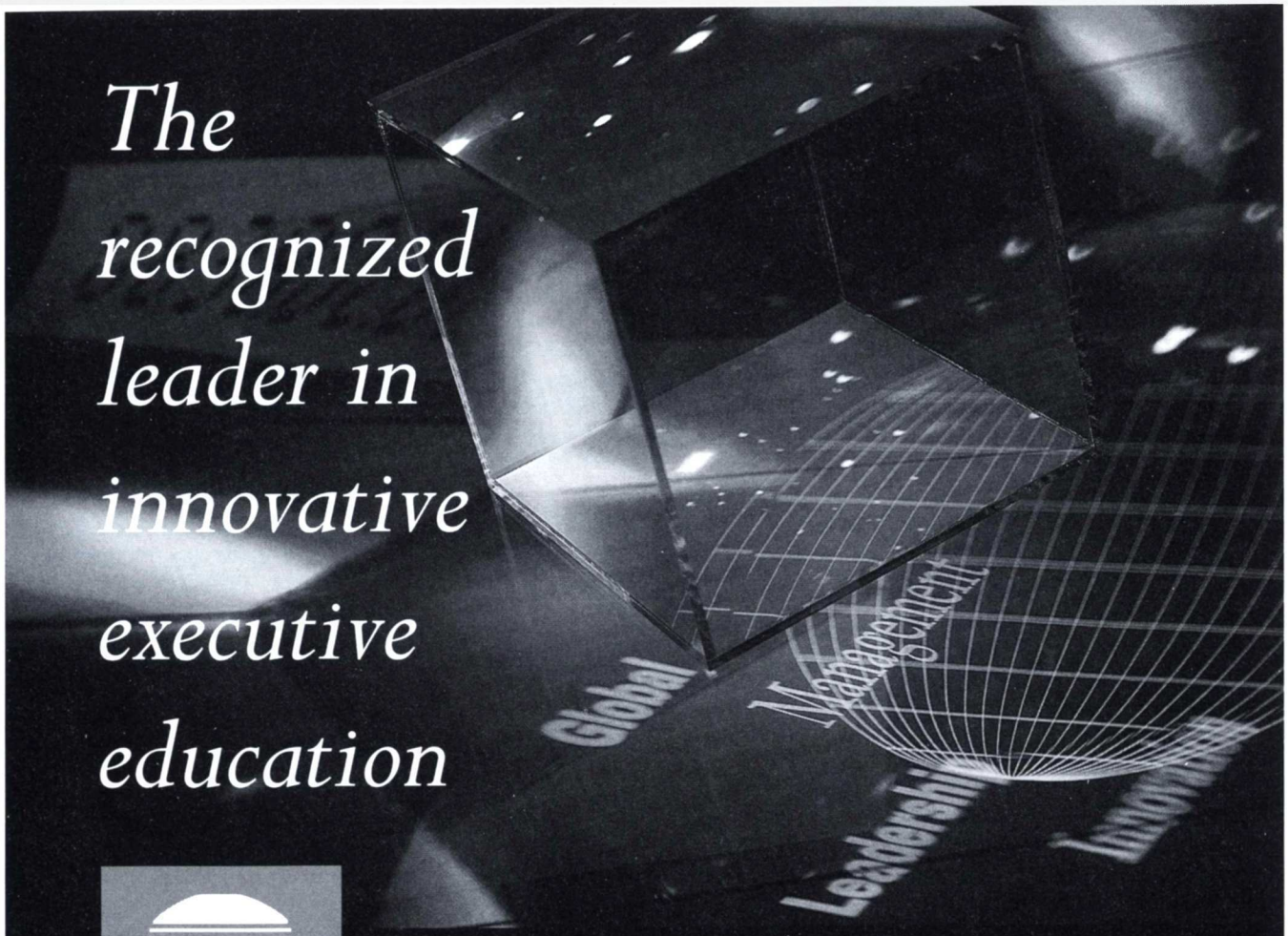
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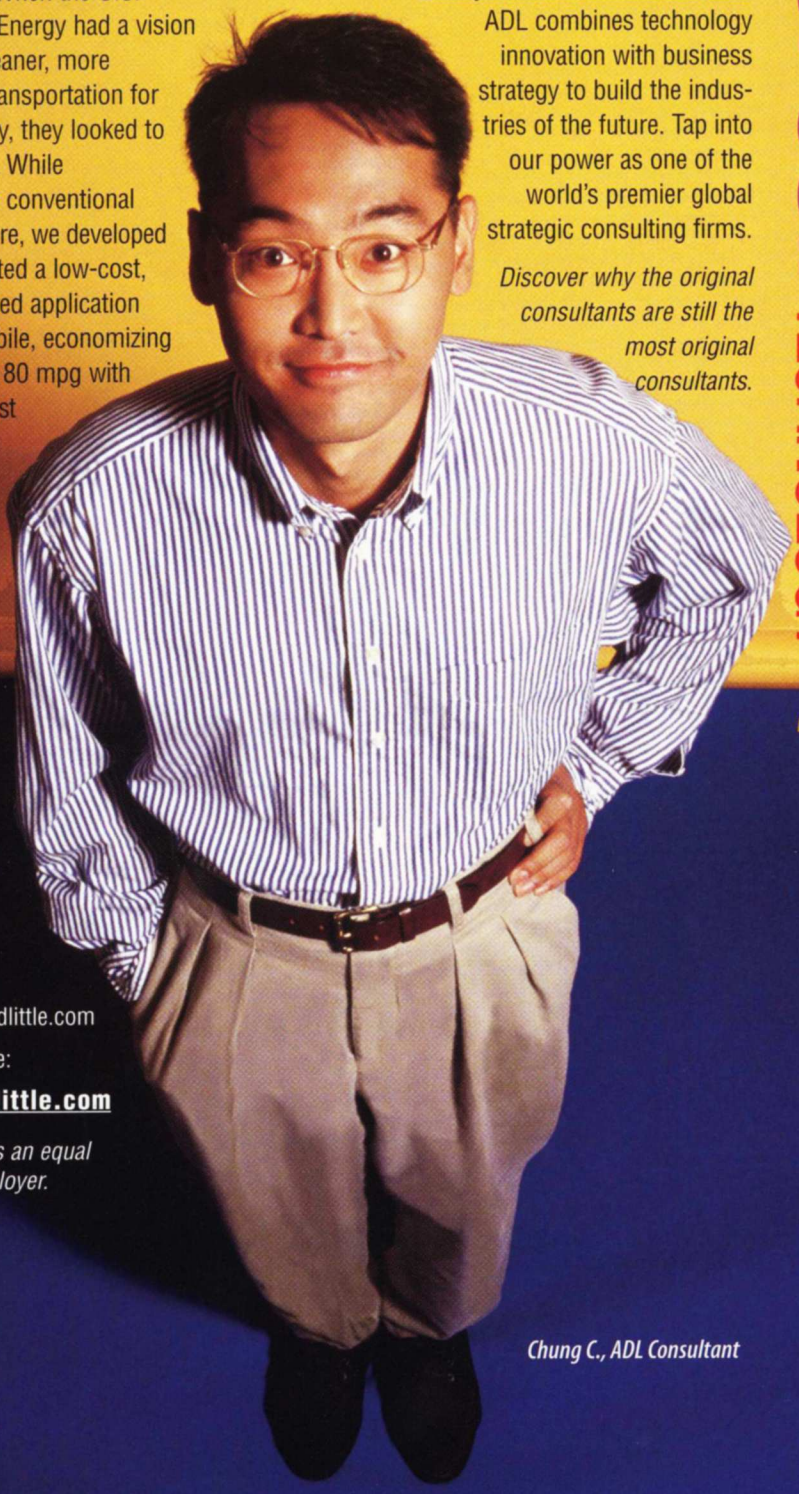
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